

EVALUATING THE EFFECTS OF THE WET AND DRY PROCESSES
FOR INCLUDING CRUMB RUBBER MODIFIER IN HOT MIX ASPHALT

Mark S. Buncher

A Dissertation
Submitted to
the Graduate Faculty of
Auburn University
in Partial Fulfillment of the
Requirements for the
Degree of
Doctor of Philosophy

Auburn, Alabama

August 30, 1995

DISTRIBUTION STATEMENT A

Approved for public release;
Distribution Unlimited

DTIC QUALITY INSPECTED 1

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

| | | |
|----------------------------------|------------------------------------|----------------------------------|
| 1. AGENCY USE ONLY (Leave blank) | 2. REPORT DATE <i>30 Aug 95</i> | 3. REPORT TYPE AND DATES COVERED |
|----------------------------------|------------------------------------|----------------------------------|

| | |
|--|--------------------|
| 4. TITLE AND SUBTITLE <i>Evaluating The Effects of the Wet and Dry Processes For Including Crumb Rubber Medication in Hot Mix Asphalt</i> | 5. FUNDING NUMBERS |
| 6. AUTHOR(S) <i>Mark S. Buncher</i> | |

| | |
|---|--|
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AFIT Students Attending: <i>Auburn</i> | 8. PERFORMING ORGANIZATION REPORT NUMBER <i>95-029D</i> |
|---|--|

| | |
|--|--|
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) DEPARTMENT OF THE AIR FORCE AFIT/CI 2950 P STREET, BLDG 125 WRIGHT-PATTERSON AFB OH 45433-7765 | 10. SPONSORING/MONITORING AGENCY REPORT NUMBER |
|--|--|

| |
|-------------------------|
| 11. SUPPLEMENTARY NOTES |
|-------------------------|

| | |
|--|------------------------|
| 12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for Public Release IAW AFR 190-1 Distribution Unlimited BRIAN D. Gauthier, MSgt, USAF Chief Administration | 12b. DISTRIBUTION CODE |
|--|------------------------|

| |
|----------------------------------|
| 13. ABSTRACT (Maximum 200 words) |
|----------------------------------|

19960124 071

| | | | |
|---------------------------------------|--|---|-----------------------------------|
| 14. SUBJECT TERMS | | | 15. NUMBER OF PAGES <i>158</i> |
| | | | 16. PRICE CODE |
| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |

EVALUATING THE EFFECTS OF THE WET AND DRY PROCESSES
FOR INCLUDING CRUMB RUBBER MODIFIER IN HOT MIX ASPHALT

Mark S. Buncher

Certificate of Approval:

Frazier Parker, Jr.
Associate Professor
Civil Engineering

E. R. Brown, Chair
Associate Professor
Civil Engineering

Prithvi S. Kandhal
Assistant Director
National Center for
Asphalt Technology

John F. Pritchett, Dean
Graduate School

Style manual or journal used: Association of Asphalt Paving Technologist

Computer software used: WordPerfect Version 5.1, Quattro Pro Version 3.0
and SAS Version 6.0

EVALUATING THE EFFECTS OF THE WET AND DRY PROCESSES
FOR INCLUDING CRUMB RUBBER MODIFIER IN HOT MIX ASPHALT

Mark S. Buncher

A Dissertation
Submitted to
the Graduate Faculty of
Auburn University
in Partial Fulfillment of the
Requirements for the
Degree of
Doctor of Philosophy

Auburn, Alabama

August 30, 1995

VITA

Mark S. Buncher, son of John and Patricia (Vuch) Buncher, was born April 5, 1960, in St. Louis, Missouri. After graduating from DeSmet Jesuit High School, he attended the University of Missouri - Rolla from 1978 to 1982, graduating *Magna Cum Laude* with a Bachelor of Science in Civil Engineering. He then attended Officer Training School and became a commissioned officer in the United States Air Force on April 22, 1983. Mark married the former Catherine L. Korte, daughter of Richard and Marilyn (Moser) Korte, on May 28, 1983. His assignments include the 97th Civil Engineering Squadron, Blytheville Air Force Base, Arkansas; the Civil Engineering Research Division of the Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico; and the Pavement Evaluation Team of the Air Force Civil Engineering Support Agency, Tyndall Air Force Base, Florida. He received his Master of Science degree in Civil Engineering from the University of New Mexico in 1986. He is a licensed Professional Engineer in New Mexico. Major Buncher was selected by the Air Force in 1992 for the PhD program at Auburn University. He will move on to Wright-Patterson Air Force Base in Ohio where he will be the Pavements Instructor at the Air Force Institute of Technology, School of Civil Engineering. Cathy and Mark have four children: Rachel (age 11), Stan (9), Mary (7), and Laura (6).

DISSERTATION ABSTRACT

EVALUATING THE EFFECTS OF THE WET AND DRY PROCESSES
FOR INCLUDING CRUMB RUBBER MODIFIER IN HOT MIX ASPHALT

Mark S. Buncher

Doctor of Philosophy, August 30, 1995
(Bachelor of Science, University of Missouri - Rolla, 1982)
(Master of Science, University of New Mexico, 1986)

172 Typed Pages

Directed by E. R. Brown

The conventional method of modifying an asphalt cement (AC) with Crumb Rubber Modifier (CRM) is to blend and "react" ground CRM particles (16 mesh and finer) in the AC, prior to mixing with the aggregate to produce hot mix asphalt (HMA). This is known as the "wet process." The "dry process", where CRM is added directly to the aggregate, has historically used larger granulated CRM particles with an objective of "rubberizing the aggregate." Recently, a few states have successfully tried a new concept of adding exclusively minus 80 mesh CRM directly to the aggregate. This in effect combines the dry process method with the wet process objective of modifying the AC. Adding the same CRM "dry" versus "wet" substantially lessens modification costs, but most feel the CRM "reaction" is very limited. The primary objective of this study was to compare the performance effects of adding the same ground CRM to HMA by the wet versus the dry process. Secondary objectives were to: 1) use the SUPERPAVE binder tests to determine the effects of ground CRM in both a reacted and unreacted state and 2) determine how

the gradation of ground CRM affects binder and mix properties in both processes.

Phase I utilized all the SUPERPAVE performance related binder tests. Four blends tested involved fully reacted CRM (nominal maximum sizes of 16, 40, 50 and 120 mesh) in a compatible AC-10, while four other blends incorporated unreacted CRM (same sizes) in the same AC-10. The CRM/AC-10 weight ratio was held constant at 15%. The AC-10 and an AC-30 from the same source were also tested as controls. The reacted blends were prepared by blending the CRM into the AC-10 at 177°C until viscosity reached a maximum level and stabilized. They were then aged according to SUPERPAVE and tested. The unreacted blends were prepared by quickly mixing the CRM into the AC-10, which was already aged according to SUPERPAVE, and immediately poured into test samples. The reacted samples simulated wet process binders, while dry process binders likely act between the reacted and unreacted samples. Test results indicated the fully reacted CRM improved all SUPERPAVE performance modes, while the unreacted CRM did the same but to a lesser degree. CRM size had very little effect relative to the overall effect of the presence of CRM.

Phase II involved testing five mixes with a 100% limestone gap-gradation: 16M wet, 16M dry, 80M wet, 80M dry, and an AC-30 control. The CRM/AC-10 ratio was again held constant at 15%, even in the design of the dry mixes. Prior to compaction, all the loose mixes were short-term aged at 152°C for four hours to simulate construction conditions. The optimum binder contents to achieve 4% voids were identical between the wet and dry mixes, for both CRM sizes. Resilient modulus at three temperatures, indirect tension, and dynamic creep results all showed no significant difference between the wet and dry mixes. They also showed the control mix was more temperature susceptible and had significantly higher resilient moduli and tensile strengths than the CRM mixes.

ACKNOWLEDGMENTS

The author would like to thank several individuals who made this academic endeavor possible and enjoyable. Dr. Ray Brown always found time in his busy schedule to discuss my research and answer questions. Dr. Frazier Parker also had an open-door policy and seemed genuinely anxious to offer assistance anyway he could. His timely advice kept this research focused on a specific objective and helped me avoid likely problems. Mr. Prithvi (Ken) Kandhal and Mr Doug Hanson were tremendous in taking the time to help. Dr. John C. Williams, although officially retired from the university, graciously agreed to serve as outside reader and devote his time. Sincere appreciation goes to those in the NCAT lab who helped in many ways: Todd Lynn, Dave Royer, Guy Savage, Johnny Turner and all the others. Special thanks to my office mate, Captain Mark Malone, for being a true comrade and friend. Finally, the author would like to thank his wife, Cathy, and children, Rachel, Stan, Mary and Laura for their love and support.

TABLE OF CONTENTS

| | |
|--|------|
| LIST OF TABLES | x |
| LIST OF FIGURES | xiii |
| CHAPTER I. INTRODUCTION | 1 |
| BACKGROUND | 1 |
| GENERAL CRM PAVEMENT TECHNOLOGY | 3 |
| SPECIFIC RESEARCH NEEDS ADDRESSED | 5 |
| CRM with SUPERPAVE Binder Tests | 5 |
| CRM Gradation Effects | 6 |
| Binder Modification with Dry Process | 7 |
| OBJECTIVES OF THIS RESEARCH | 9 |
| SCOPE AND APPROACH | 9 |
| Phase I | 9 |
| Phase II | 11 |
| CHAPTER II. LITERATURE REVIEW | 13 |
| INTRODUCTION | 13 |
| SCRAP TIRE PROBLEM | 14 |
| ISTEA SECTION 1038 SPECIFICS | 16 |
| CRM TYPES | 17 |
| ASPHALT RUBBER (AR) | 18 |
| Production | 18 |
| Storability | 20 |
| Compatibility | 21 |
| Improved Binder Properties | 22 |
| PERFORMANCE CLAIMS ON CRM MIXES | 23 |
| Wet Process | 23 |
| Dry Process | 25 |
| WET PROCESS MIX DESIGNS | 25 |
| General Considerations | 25 |
| McDonald Technology | 26 |
| Continuous Blending Technology | 27 |

| | |
|--|--------|
| DRY PROCESS MIX DESIGNS | 28 |
| General Considerations | 28 |
| PlusRide | 28 |
| TAK System (Original Generic Dry) | 29 |
| New Generic Dry System | 30 |
| CONSTRUCTION OF CRM MIXES | 31 |
| FIELD PERFORMANCE HIGHLIGHTS | 31 |
| McDonald | 32 |
| Continuous Blending Technology | 33 |
| PlusRide | 34 |
| TAK System | 34 |
| New Generic Dry System | 34 |
| CHAPTER III. TEST PLAN | 36 |
| FOCUS ON A SPECIFIC OBJECTIVE | 36 |
| DEVELOPMENT OF A GENERAL PLAN | 37 |
| PHASE I TEST PLAN OUTLINE | 39 |
| PHASE II TEST PLAN OUTLINE | 43 |
| SELECTION OF SPECIFICS AND RATIONALE | 46 |
| Asphalt Cement | 46 |
| CRM | 47 |
| Preparation of Binder Blends and AR | 49 |
| CRM/AC-10 Ratio | 50 |
| Aggregate and Gradation | 51 |
| Mix Design Elements | 54 |
| Phase I Binder Tests | 57 |
| Phase II Mix Tests | 59 |
| CHAPTER IV. TEST DESCRIPTIONS | 60 |
| PHASE I | 60 |
| Dynamic Shear Rheometer (DSR) | 60 |
| Bending Beam Rheometer (BBR) | 62 |
| Direct Tension Test (DTT) | 62 |
| PHASE II | 63 |
| Indirect Tension (IT) | 63 |
| Resilient Modulus (RM) | 63 |
| Creep | 65 |

| | |
|--|-----|
| CHAPTER V. PHASE I TEST RESULTS AND ANALYSIS | 66 |
| DSR TESTING | 67 |
| G*, δ and Temperature Relationships | 67 |
| SUPERPAVE Criteria | 78 |
| CRM Gradation Effects | 86 |
| Aging Ratios | 90 |
| BBR and DTT TESTING | 91 |
| Results at -18°C | 91 |
| SUPERPAVE Criteria | 93 |
| "QUASI" SUPERPAVE GRADE | 99 |
| CHAPTER VI. PHASE II TEST RESULTS AND ANALYSIS | 101 |
| MIX DESIGNS | 101 |
| Specific Gravity of Mix Components | 102 |
| Optimum Binder Content Selection | 103 |
| RM TESTS | 107 |
| RM Values at Each Temperature | 107 |
| Aging | 110 |
| Temperature Susceptibility | 111 |
| IT TESTS | 117 |
| CREEP TESTS | 120 |
| STATISTICAL CONTRASTS | 121 |
| CHAPTER VII. CONCLUSIONS AND RECOMMENDATIONS | 123 |
| PHASE I CONCLUSIONS | 123 |
| PHASE II CONCLUSIONS | 124 |
| RECOMMENDATIONS | 126 |
| REFERENCES | 128 |
| APPENDIX A. Preparation of AR | 133 |
| APPENDIX B. Individual DSR Test Results | 139 |
| APPENDIX C. Individual BBR and DTT Results | 147 |
| APPENDIX D. Individual RM Test Results | 150 |
| APPENDIX E. Individual IT and Creep Test Results | 155 |

LIST OF TABLES

| Number | Description | Page |
|--------|--|------|
| 2.1 | Typical CRM Prices by Particle Size | 18 |
| 3.1 | Phase I Primary Binder Blends Tested | 40 |
| 3.2 | Phase I Test Information | 40 |
| 3.3 | Supplemental Binder Blends Which Had Limited Testing | 42 |
| 3.4 | Phase II Mixes Tested | 43 |
| 3.5 | Phase II Mix Design and Sample Preparation Highlights | 44 |
| 3.6 | Phase II Test Information | 44 |
| 3.7 | Sieve Analysis of CRM Used | 49 |
| 3.8 | Actual Aggregate Gradation Used | 54 |
| 5.1 | Test Temperature Extremes at Which SUPERPAVE Criteria with DSR Were Met | 84 |
| 5.2 | TFO Aging Ratios on Control and Reacted Blends | 91 |
| 5.3 | BBR and DTT Results at -18°C (averages and standard deviation) | 92 |
| 5.4 | Auxiliary BBR Results at -12°C and -24°C (averages) | 94 |
| 5.5 | Test Temperature Minimums at Which SUPERPAVE Criteria with BBR Were Met | 98 |
| 5.6 | Summary of Binder Blends' Acceptable Temperature Performance Range | 99 |

| Number | Description | Page |
|--------|---|------|
| 6.1 | Effective Specific Gravity of Aggregate Determined for Each Mix | 102 |
| 6.2 | Optimum Binder Contents from Independent Mix Designs | 103 |
| 6.3 | Average RM Values at 40°C | 108 |
| 6.4 | Average RM Values at 25°C | 108 |
| 6.5 | Average RM Values at 5°C | 109 |
| 6.6 | LT Aging Ratios (averages and standard deviation) in terms of RM | 110 |
| 6.7 | Regression Slopes of Corrected log RM vs Temperature Plots | 116 |
| 6.8 | Regression Slopes of Uncorrected log RM vs Temperature Plots | 116 |
| 6.9 | Average ITS Results at 25°C | 118 |
| 6.10 | Average IT ϵ_f Results at 25°C | 119 |
| 6.11 | Average Creep Results at 60°C | 120 |
| 6.12 | Contrasts between CRM vs No CRM Mixes, Wet vs Dry Mixes, and 16M vs 80M Mixes | 122 |
| B.1 | DSR Results on Original (No Aging) Blends | 140 |
| B.2 | DSR Results on Short-Term Aged (TFO) Blends | 142 |
| B.3 | DSR Results on Long-Term Aged (PAV) Blends | 144 |
| B.4 | DSR Results on SUPPLEMENTAL Blends which have been Long-Term Aged | 146 |

| Number | Description | Page |
|--------|--|------|
| C.1 | BBR Results, at -18°C | 148 |
| C.2 | Direct Tension Results, at -18°C | 149 |
| D.1 | RM Results on 4% VTM Samples | 151 |
| D.2 | RM Results on 7% VTM Samples Before LT Aging | 152 |
| D.3 | RM Results on 7% VTM Samples After LT Aging | 153 |
| D.4 | Long Term Aging Ratios of Samples | 154 |
| E.1 | Individual Indirect Tension Test Results | 156 |
| E.2 | Individual Creep Test Results | 158 |

LIST OF FIGURES

| Number | Description | Page |
|--------|---|------|
| 2.1 | Schematic of Typical Wet Process (4) | 19 |
| 3.1 | Flowchart of Blending, Aging and Testing, Phase I | 41 |
| 3.2 | Flowchart of Testing, Phase II | 45 |
| 3.3 | Photo of 16M and 80M CRM | 48 |
| 3.4 | Gap-Gradation Selected Compared to Kansas and California Gap-graded Specification Limits | 53 |
| 5.1 | G^* vs Temperature of 16M and Control Blends | 69 |
| 5.2 | δ vs Temperature of 16M and Control Blends | 70 |
| 5.3 | G^* and δ vs Temperature of 40M and Control Blends | 71 |
| 5.4 | G^* and δ vs Temperature of 50M and Control Blends | 72 |
| 5.5 | G^* and δ vs Temperature of 120M and Control Blends | 73 |
| 5.6 | δ vs G^* of 16M, 40M and Control Blends | 76 |
| 5.7 | δ vs G^* of 50M, 120M and Control Blends | 77 |
| 5.8 | Tenderness Parameter vs Temperature of All 10 Blends | 80 |
| 5.9 | Rutting Parameter vs Temperature of All 10 Blends | 81 |
| 5.10 | Fatigue Parameter vs Temperature of 16M, 40M and Control Blends | 82 |

| Number | Description | Page |
|--------|---|------|
| 5.11 | Fatigue Parameter vs Temperature of 50M, 120M and Control Blends | 83 |
| 5.12 | Relationship of Rutting Parameter to CRM Particle Size | 88 |
| 5.13 | Relationship of Fatigue Parameter to CRM Particle Size | 89 |
| 5.14 | BBR Stiffness (S) vs Temperature of All 10 Blends | 96 |
| 5.15 | BBR Creep Rate (m) vs Temperature of All 10 Blends | 97 |
| 6.1 | VTM vs Trial Binder Content for CNTRL and 16M Wet Mix Designs | 105 |
| 6.2 | VTM vs Trial Binder Content for 16M Dry Mix Design | 105 |
| 6.3 | VTM vs Trial Binder Content for 80M Wet Mix Design | 106 |
| 6.4 | VTM vs Trial Binder Content for 80M Dry Mix Design | 106 |
| 6.5 | Average RM vs Temperature for 4% VTM Samples | 112 |
| 6.6 | Average RM vs Temperature for 7% VTM Samples Before LT Aging | 113 |
| 6.7 | Average RM vs Temperature for 7% VTM Samples After LT Aging | 114 |
| A.1 | Reaction Monitoring with Brookfield Viscometer | 138 |

CHAPTER I. INTRODUCTION

This chapter introduces the background of Crumb Rubber Modifier (CRM) as an additive to hot mix asphalt (HMA) and why it has become an important topic in the pavements industry. Additional information on general CRM pavement technology is presented to help the reader understand the three specific research needs which this effort addresses. After discussing these needs, the objectives, which mirror the three needs, are listed. Finally, the scope and research approach are discussed.

BACKGROUND

Pavement engineers are continually seeking new ways to design and build roads and airfields to last longer. Thicker base and surface layers, better drainage, or improved pavement materials may be used to extend a pavement's life. For HMA, a common method of improving performance is to use additives to modify the properties of the mix. There are a number of different HMA additives available which can be introduced directly to the asphalt cement (AC) as a binder modifier, or can be added to the mixture with the aggregate. Some of these additives improve various aspects of performance while others do not.

Improving field performance generally means reducing or delaying the three general HMA distress types: permanent deformation such as rutting or shoving, cracking from either repeated loads (fatigue) or cold-temperature contraction, and disintegration such as raveling and stripping. Rubber material, one of ten generic

asphalt additive types, has been promoted and used to decrease all three of these distress modes (1). Rubber can be added in the form of latex, or as CRM whose primary constituent is scrap tire rubber. Many believe if the binder becomes more elastic or rubber-like, the binder and the mix will be less temperature sensitive. This means in low temperature conditions, the modified binder and mix should be more flexible, thereby reducing thermal cracking problems. In high temperature conditions where rutting and shoving are a concern, the rubber should increase the binder and mix stiffness to reduce deformation potential. Promoters of rubber have claimed it increases the elasticity of the binder and mix, improving fatigue characteristics. It has also been declared that rubber improves adhesion between the binder and the aggregate, minimizing raveling and/or stripping.

Of course these alleged benefits are not free. Generally, the cost of HMA modified with CRM is 1.2 to 3 times the cost of a conventional mix, depending on the modification method, mix design, and size of project (2, 3, 4, 5). This increase is due to a number of factors other than the additional material cost of the rubber. Production costs may increase because of specialized blending equipment, additional energy costs associated with higher blending and mixing temperatures, payment of a patent fee for a proprietary design system, and a higher contractor profit margin to cover the uncertainties of producing, placing and compacting the modified mix. In the past, CRM, like all modifiers, was expected to be cost-effective before an agency would regularly specify its use, other than test sections.

This logical design strategy of cost-effectiveness changed when the United States Congress, in an effort to reduce the solid waste management problem of scrap tires, passed the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). Section 1038 of ISTEA mandates that each state will utilize a certain amount of recycled tire rubber every year in their HMA and/or asphalt binder for federally

funded highway projects, or have federal money withheld for future projects. Although this was suppose to be effective in fiscal year (FY) 1994, two one-year moratoriums have been passed which now delays the measure until the start of FY 1996. Non-compliance is not a likely option for states because of their dependency on federal highway construction money. As of July 95, a repeal of the CRM mandate was included in National Highway Systems Bill, passed by the Senate in June 95 but still being debated in the House. The bill would also direct federal grants of up to \$500,000 be made available to states for developing programs to use CRM in HMA. If the bill is delayed or does not pass, another one-year moratorium for 1996 has been proposed.

As a result of ISTEA, a surge of interest has developed in CRM technology. Prior to 1991, only a few states had experimented with CRM in HMA and fewer were using it on a regular basis. Presently, most states have constructed at least some test sections using CRM in HMA. The performance of these test sections and other laboratory research will be used by states to develop their CRM utilization plans to meet ISTEA mandates. States are taking different approaches. Some do not believe in the merits of using CRM and are looking for the least expensive way to meet ISTEA quotas without adversely affecting the mix. Others want to optimize the benefits derived from the CRM while of course keeping their modification costs down. It is critical that the technology base of using CRM in HMA be understood and expanded so states can make technically sound and financially wise decisions.

GENERAL CRM PAVEMENT TECHNOLOGY

CRM is produced from scrap tire rubber through mechanical grinding and shearing. The tire rubber is reduced in particle size ranging from $\frac{1}{4}$ -inch (6.3 mm)

to as small as 200 mesh (M) (.08 mm), with the finer CRM generally costing more due to the additional grinding required.

The two methods for incorporating CRM into HMA are referred to as the "wet" and the "dry" processes. The wet process adds the CRM to the AC and blends or "reacts" the two prior to mixing the binder with the aggregate, while the dry process adds the CRM directly to the aggregate prior to introducing the AC. In the most commonly used wet process technology, called McDonald, the CRM is relatively small in size, with a typical maximum particle size of 16M (1.2 mm). To fully react the CRM, blending time is typically 30 to 60 minutes at temperatures between 175 and 190°C, which are higher than conventional mixing temperatures (4, 6). The CRM added by the original dry process, tradename PlusRide, is much coarser, with a maximum particle size of $\frac{1}{4}$ -inch (6.3 mm) and approximately 65% (by weight) larger than 10M (2.1 mm) (7, 8). The modified binder product of the wet process is called asphalt rubber (AR) while the mixture product of the dry process is called Rubber Modified HMA (RUMAC). These are industry accepted terms. This paper uses the term "CRM mix" to refer to the mixture product of either process.

The objectives of the wet and dry methods were originally very different. The sole objective of the wet process has always been binder modification. Conversely, the primary reason for using the original dry process system, PlusRide, is to replace a portion of the aggregate with granulated CRM particles, achieving a "flexible aggregate" effect. A secondary benefit of binder modification is recognized as being possible, but not believed to be substantial. A new dry process technology, developed by Takallou in the late 1980's, utilizes a combination of large granulated particles to rubberize some of the aggregate and small ground CRM which is intended to "partially modify" the binder (9, 10). Recently, three states (Kansas, Arkansas, and Oklahoma) have tried adding only the finer ground CRM (80M

nominal maximum size) with the dry process (11). Material engineers are unsure if the fine CRM particles are reacting as they do in the wet process to modify the binder, partially reacting, or not reacting at all and acting simply as inert filler? Many believe adding the fine CRM "dry" achieves no benefits because the CRM is not able to react once the AC is in thin films coating the aggregate, limiting its availability to react with the CRM. In addition, many believe the mixing temperatures of the dry process are not high enough for a reaction to occur, since typical wet process blending temperatures are higher.

There are many variables associated with the performance of CRM mixes other than the process and technology used. Many are not well understood. The amount, type and gradation of CRM in the mix all likely have an influence on how the binder is modified as well as the interaction taking place between the CRM particles and the aggregate. The amount of time the CRM is in contact with the AC and the temperature is important for both the wet and dry processes. In the wet process, contact time and temperature are controlled during blending. In the dry process, mixing temperature and storage time of the mix are the variables which can be controlled in the field. Different AC sources have different compatibilities with CRM which determine how much reaction occurs. Aggregate gradation is also a key factor as dense graded, open graded, and gap graded mixes have all been used with CRM.

SPECIFIC RESEARCH NEEDS ADDRESSED

CRM with SUPERPAVE Binder Tests

An obvious research need for expanding CRM technology was created when the Strategic Highway Research Program (SHRP) spent over \$50 million to improve performance of asphalt binders and mixtures. A new performance-based binder

specification and associated binder tests were developed to provide fundamental material properties needed to better predict performance (12). Prior to SHRP, empirically based binder tests were used. The SHRP program terminated in 1993, and the new specification and tests, referred to as SUPERPAVE, should be fully implemented nationally within a few years, changing entirely the way binders are graded. SUPERPAVE tests are considered state-of-the-art within the asphalt industry and are supposedly transparent to whether the binder is modified or not. Most of the older empirical tests are not applicable to modified binders. This transparency of the SUPERPAVE tests allows researchers to see the effect asphalt modifiers have with regards to predicted performance. Since these tests and associated equipment did not become available until 1993, there is a limited database of SUPERPAVE binder test results demonstrating the effects of CRM.

CRM Gradation Effects

CRM gradation is understood to be an important variable in how quickly the binder is modified as well as the interaction which takes place between the aggregate and the CRM. Many states are paying substantially more for the finer CRM because it has been found to react quicker than larger CRM (6), enhancing production of AR with the wet process (13) and hypothetically increasing the amount of binder modification occurring with the dry process (10). This is a result of the CRM surface area in contact with the AC increasing as the gradation becomes finer. It is also understood that if the CRM particles are large enough, they may bridge the stone aggregate and affect the compaction of the mix due to rebound of the rubber. What is not understood is how the CRM gradation will affect the modified binder properties, for reacted and unreacted CRM.

Binder Modification with Dry Process

The predominant feeling is if the objective of using CRM is binder modification, the wet process should be used. A 1992 survey on in-place CRM mix sections showed roughly twice as many designs used the wet process versus the dry (2). Many states are skeptical of the dry process because some "PlusRide" test sections (with the larger granulated CRM) constructed in the past have had premature raveling problems (3, 4). However, where smaller ground CRM has been added dry, raveling has not occurred and performance has been satisfactory (7, 14, 15, 16). The amount of binder modification that occurs with any dry process technology is unknown. Also, the effect of any unreacted fine CRM in terms of modifying the AC and the mix is unknown. These questions have become very relevant as the new approach of adding only finely ground CRM by the dry process has started. A report prepared for Congress by the Federal Highway Administration (FHWA) and Environmental Protection Agency (EPA) in 1993 on the use of CRM in HMA stated:

"It should be determined whether or not the product of the dry process can be made equivalent to the product of the wet process based on the fineness and quantity of CRM used in the mixture (2)."

There has been no research in the area of quantifying the difference in performance between adding CRM to HMA with the wet process versus the dry process for four reasons, the first three of which have already been mentioned. First, complying with Section 1038 of ISTEA is a relatively new concern. Secondly, the past objectives of both the wet and dry processes were different. Thirdly, adding the finely ground CRM with the dry process is a relatively new concept which many

believe offers no improvement to the mix. Lastly, it is impossible to model with binder tests any reaction taking place between the CRM and AC in the dry process, as can be done with AR in the wet process. Since the CRM in the dry process only comes in contact with the AC with the presence of aggregate, mix tests must be used. This contact is different than the contact occurring in the wet process because the AC film thickness coating a CRM particle in the dry process is small relative to the film thickness occurring during blending operations of the wet process. For example, a typical average AC film thickness coating the aggregate of a conventional mix is only 1/20th the diameter of a 80M CRM particle. This thin coating may reduce the amount of AC available to react with the CRM particle.

Significant cost savings can be achieved by adding fine CRM with the dry versus wet process (2, 3). The wet process requires special blending equipment to react the CRM with the AC at elevated temperatures for a specified period of time. The blending process not only requires specialized equipment, but additional manpower to open the bags of CRM and add the material. With the dry process, the CRM is usually brought to the job site in bulk, blown into a mineral filler silo, and then fed into the drum by auger and belt, just like dry additives or mineral filler would be added. Many states already have the mineral filler silos set up at their plants. No additional people are required except to calibrate the silo auger at the beginning of production. Another factor driving the cost of the wet process higher than the dry is that AR, once blended, is thought to have a typical shelf life of 24 hours (6, 17), causing HMA producers to take a greater risk if an unexpected shutdown at the plant or jobsite occurs. Production of the AR may also be slower than needed to meet the demands of the job or capabilities of the plant. Stroup-Gardiner reported an average increase in cost of 60% to a dense-graded mix using the wet process, while only a 20% increase with the dry process, where the

same CRM size and quantity were used with both processes and no royalty fees were included (5).

OBJECTIVES OF THIS RESEARCH

The objectives of this study addressed the three specific research needs discussed in the previous section. The primary objective was to:

Compare the effects of adding CRM to HMA by the wet process versus the less expensive dry process, given the same CRM type, size and amount. Compare both processes to a mix without CRM.

Secondary objectives were to:

- 1) use the SUPERPAVE binder tests to determine if the addition of CRM, both in a reacted and unreacted state, improved binder properties.
- 2) examine the effects of ground CRM gradation on binder and mix properties in both the wet and dry processes.

SCOPE AND APPROACH

This research was sponsored by the United States Air Force and the National Center for Asphalt Technology (NCAT). The lab work was divided into two parts, Phase I and Phase II. It was performed in the NCAT lab almost exclusively by the author. A literature review was also conducted.

Phase I

The SUPERPAVE performance-related binder tests were utilized in Phase I: the Dynamic Shear Rheometer (DSR), the Bending Beam Rheometer (BBR), and the Direct Tension Test (DTT). A total of ten blends were tested: four

fully reacted AR blends, four unreacted blends and two controls (an AC-10 and AC-30 from the same source). The reacted blends were prepared by blending and fully reacting each of four CRM sizes (16, 40, 50, or 120M nominal maximum size) into the AC-10. After appropriate SUPERPAVE aging, DSR, BBR and DTT samples were prepared and tested. The unreacted blend samples were prepared by blending each of the four CRM sizes into the appropriately aged AC-10, quickly mixing, and immediately pouring the blend into test samples, limiting the temperature and time the CRM and AC were in contact.

Phase I showed, in terms of the SUPERPAVE binder properties, the effects of adding CRM to an AC, both when the CRM was allowed to fully react as occurs in the wet process, and when the CRM was unreacted, which is the worst-case scenario in the dry process. Many believe the CRM is "partially" reacted in the dry process, especially if the CRM is fine enough. Although no binder testing can determine exactly how much reaction occurs with the dry process or what the true effect is, this approach demonstrated both possible extremes. The true effect likely falls between the reacted and unreacted results of each CRM gradation as demonstrated in this research. This study also revealed how much reaction occurs in the Thin Film Oven test (short-term aging) and the Pressure Aging Vessel test (long-term aging).

The effects of CRM gradation were examined by testing four sizes. One CRM type and one AC source were used. The AC source was known to be compatible with the CRM by its history of improved binder properties with the addition of CRM. This is due to the AC source having a sufficient quantity and type of aromatic oils available to react with the CRM. The CRM/AC-10 ratio was held constant at 15% (by weight) for all eight of the rubberized blends.

The SUPERPAVE binder specification was used as a guide to grade and compare the ten blends. Relative performance in terms of tenderness, rutting, and fatigue was predicted with the DSR. They also indicated which blends were more elastic versus viscous, were least temperature sensitive, and aged the slowest. Relative cold-temperature performance was predicted with the BBR and DTT.

Phase II

Mixture tests were conducted in Phase II. The five mixes tested were identical except for different AC/CRM binder blends: the wet process using either 16M or 80M CRM, the dry process using 16M or 80M CRM, and one control as an AC-30 with no CRM. Variables evaluated within the four CRM mixes were the process (wet vs. dry) and the CRM gradation (16M vs. 80M). The control was tested to compare the four rubberized mixes to one without rubber.

Independent mix designs were performed for each of the five mixes to determine the optimum binder content (total weight of AC and CRM) to provide 4% air voids (VTM). The SUPERPAVE gyratory compactor was used for compacting the 100 mm diameter specimens. The aggregate was gap-graded 100% limestone. The CRM/AC-10 weight ratio of both the wet and dry mixes was again held constant at 15%. The wet process samples were prepared with a fully reacted AR as the binder, while the dry process samples were prepared by adding the appropriate amount of CRM to the heated aggregate and briefly mixing prior to the addition of the AC-10. Prior to compaction, all the loose mixes were short-term aged at 152°C for four hours, simulating the aging and possible reaction which may occur during pugmill mixing and storage in a silo and bed of a haul truck.

After the mix designs, test samples with 4% VTM were produced at optimum. In addition, 7% VTM samples were produced at optimum but by a reduced number of gyrations. Some of these were long-term aged in accordance with SUPERPAVE.

Resilient modulus tests were performed at 5, 25, and 40°C to evaluate temperature susceptibility. Indirect tensile tests (strain to failure) were used to examine cracking potential of the mixes. Dynamic creep testing was conducted to determine rutting potential. The resilient modulus and indirect tension tests were performed on aged and unaged samples with 7% VTM to examine aging.

CHAPTER II. LITERATURE REVIEW

The scope of this review covers the use of CRM as an additive in HMA mixtures, with both the wet and dry processes. Emphasis is placed on the effects of added CRM on binder and, ultimately, mix properties. Material, design and construction considerations are discussed. Only the use of CRM in paving mixtures is examined. Other pavement material applications such as the use of CRM in surface treatments, stress absorbing membrane interlayers, and joint and crack sealants will not be discussed.

INTRODUCTION

Because of the surge of interest in CRM technology, there have been several thorough literature reviews conducted on the subject within the past few years (3, 4, 18). In addition, the FHWA in 1993 conducted several two-day regional CRM workshops across the country to provide the highway community, both government and industry, with a better understanding of the technology and practices presently available. The handout notes from these workshops were organized by subject (sessions) and written by experts (5, 6, 7, 8, 19, 20). These notes provide an excellent and detailed review of the subject. In 1994, a catalog and software database was developed by the University of Nevada-Reno under the National Cooperative Highway Research Program (NCHRP) which lists over 700 publications concerning the use of CRM in highway applications (21). This is by far the most comprehensive listing developed covering the topic. The university will continue updating the

catalog and database and will make these publications available upon request. The software database provides a "one-stop shopping list" to identify and acquire publications concerning a general category, specific keyword, or state. This catalog and database, as well as the FHWA workshop notes, are recommended for more detailed information.

The purpose of this chapter is not to duplicate the inclusive efforts mentioned in the previous paragraph, but rather to provide the reader an adequate background of CRM technology so as to understand this research effort and its significance to the technology. Along with a general overview on the use of CRM in HMA, more detailed information is furnished on specific aspects of the technology which this research focuses on. The information summarized in this chapter provided the basis for formulating the test plan described in the next chapter.

SCRAP TIRE PROBLEM

Discarded scrap tires have become a growing environmental concern in the United States. Forty-nine states have enacted legislation regulating their disposal. Approximately 285 million worn tires are disposed of annually in our country. About 100 million of these waste tires annually are either resold, retreaded, or used in other reuse applications such as fuel for combustion or highway material applications. This leaves approximately 185 million tires each year to be stockpiled, placed in landfills or illegally dumped (11).

The EPA has estimated that 2 to 3 billion tires are currently in stockpiles at various locations across the country. This represents about 1 percent of our country's total municipal solid waste by weight (22). Stockpiles are a fire, health and environmental hazard. If the tires are ignited, stockpiles generate a fire which produces a large amount of toxic black smoke and is extremely difficult to extinguish.

Besides being unsightly, stockpiled tires accumulate water due to their shape which breeds mosquitos.

Burying tires in landfills is not an easy solution either. As environmental regulations become stricter, landfills rarely accept whole tires. Due to a tire's shape which traps air and landfill gases, buried tires have a tendency to float to the surface. This can cause damage to landfill liners and the fill cover. Cutting tires prior to burial is a potential solution, but shredding adds to the disposal cost and it still uses considerable landfill volume, something which is becoming scarcer each day (3).

Section 1038 of ISTEA was enacted in 1991 in hopes of relieving part of the scrap tire problem. In Section 1038's original form, and assuming all the states met the provisions, estimates of the total waste tires consumed annually starting in 1997 was between 68 to 120 million (22). This compared to the 1991 consumption from pavement applications of only 1 to 2 million tires per year (4). Obviously Section 1038 alone will not eliminate the 2 to 3 billion tires in our stockpiles, but it could make a significant reduction in the 185 million of excess tires produced annually. If certain applications of CRM mixes can be shown to be cost effective, a still greater contribution to the scrap tire problem is possible. Unfortunately, only about half of the tire material can be used to produce CRM, with the remaining steel, fiber, and nonseparable rubber having to be disposed. Many CRM suppliers use tire buffings and not the entire tire as the raw material to produce CRM.

As of July 1995, the National Highway Systems Bill, passed by the Senate in June but being deliberated in the House, included a provision to repeal Section 1038's mandate to use CRM. It also directs the FHWA to conduct research to develop testing procedures and performance grade classifications for CRM binders, and to make grants of up to \$500,000 available to states for developing programs to use CRM in HMA.

ISTEA SECTION 1038 SPECIFICS

The FHWA published final implementation guidance of Section 1038 in July, 1993 (23). The MUR of CRM mixes was to have been 5% for FY 1994, 10% for FY 1995, 15% for FY 1996 and 20% for FY 1997 and each FY thereafter. As mentioned earlier, two one-year moratoriums have delayed the enforcement of Section 1038 until 1996. If the 1995 National Highway Systems Bill, which repeals the CRM mandate, is delayed or not approved, another one-year moratorium for 1996 is being considered. However, if none of these actions are passed by Congress by the start of FY 1996, Section 1038 would be enforced with a MUR of 15%.

The quantity of CRM required to satisfy Section 1038 is calculated from the equation:

$$R = \text{MUR} \times (20M + 300S) , \text{ where}$$

R = lbs of CRM required to satisfy Section 1038,

MUR = minimum utilization required, as a decimal (ie .15 for FY 1996),

M = total tons of federal-aid HMA awarded during the FY,

S = total tons of federal-aid hot spray applied binder awarded during the FY.

As the equation shows, the MUR is based on 20 lbs of CRM per ton of HMA (1%), and 300 lbs of CRM per ton of hot spray applied binder (15%). However, if the CRM concentration is greater than these, the excess is credited towards the utilization. Thus, a state may choose to rubberize less HMA than the MUR using a CRM concentration greater than 1% by weight of mix, or to rubberize more HMA at a lower CRM concentration. The cumulative weight of CRM is totaled from any highway project in the state. The 1993 guidance (23) also clarified how other recycled materials used in HMA can be considered in meeting up to 5% of the MUR.

CRM TYPES

Crumb Rubber Modifier is produced chiefly from scrap tire rubber and is composed primarily of natural and synthetic rubbers as well as carbon black. Car tires tend to have more synthetic rubber while truck tires tend to have more natural rubber. This difference in chemical composition has decreased over the years with new tire technology. It has been stated that typical bulk CRM produced on today's market is relatively uniform in composition (4). CRM is not normally produced based on a specific blend of tires. Rather, the size, shape and texture of the CRM particles are specified. These properties are important because they control the relative surface area of the material which influences the reaction of the rubber with the AC. The size, shape and texture desired will determine the type of processing required.

There are several processing methods which produce CRM. The most common is the crackermill process, where the rubber is ground between corrugated steel drums. The result is torn, irregularly-shaped particles with a relatively large surface area in the $\frac{1}{4}$ -inch to 40M (4.7-.42 mm) range. Rubber produced by this method is called "ground" rubber and often used in the wet process where the large relative surface area expedites reaction. A micromill using wet grinding can further process CRM into finer particles smaller than 40M. Rouse Rubber Industries claims to have a patent for this wet grinding method which produces CRM that is called by their tradename, UltraFine. The dispersion and reaction rate is the greatest with finer CRM gradations, but material cost is driven up considerably. Granulating is another process which chops the rubber between revolving steel plates, resulting in relatively smooth, cubical shaped particles sized between $\frac{3}{8}$ and .1 inch (9.4-2.5 mm). This "granulated" rubber has a smoother surface and is frequently used in the dry process when reaction is not the primary objective.

CRM is most often shipped in 50 to 60 lb (23-27 kg) paper or plastic bags stacked on pallets. Large 1000 to 2000 lb (453-906 kg) containers have been used which dispense the CRM from the bottom. The CRM may also be shipped in bulk, but segregation of the smaller sized particles to the bottom may be a problem. Typical price ranges, acquired from discussions with several users and suppliers, are shown below in Table 2.1.

Table 2.1 Typical CRM Prices by Particle Size

| CRM Particle Size | Cost per pound |
|-------------------------|----------------|
| $\frac{1}{4}$ - .1 inch | \$.10 - .20 |
| 10 - 20 mesh | \$.14 - .24 |
| 30 - 40 mesh | \$.15 - .25 |
| 40 - 80 mesh | \$.20 - .40 |

ASPHALT RUBBER

Production

Asphalt Rubber (AR), composed primarily of reacted CRM and AC, is the end-result binder of the wet process. Figure 1 is a schematic of the typical McDonald wet process showing how the CRM and AC are metered into a blending unit and then transferred to a reaction tank. Normally, bags of CRM are opened manually and the CRM is poured onto a conveyer which feeds the blender hopper. The blending unit uses low shear mechanical mixing and is heated between 175 to 205 °C (348 to 400 °F). The blended mixture is then immediately transferred into a

heated reaction tank where a constant temperature of 175 to 190°C (348 to 375°F) is maintained. An agitation system keeps the CRM dispersed in the AC and circulates the blend to prevent coking at hot spots in the tank. After the reaction period, the batch of AR is ready to be pumped and utilized as a HMA binder (7).

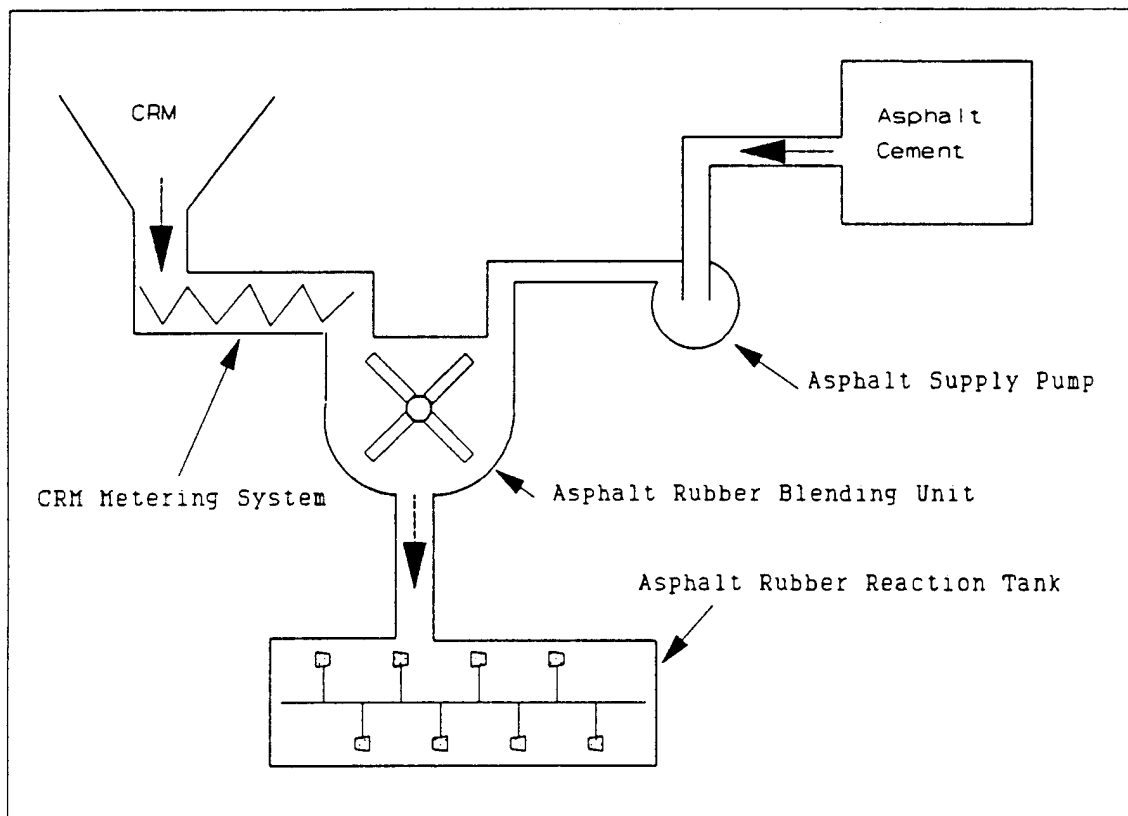


Figure 2.1 Schematic of a Typical Wet Process (4)

Even though the word "reaction" is used to describe the change in binder properties when CRM is introduced, the change is more physical than chemical. The CRM does not dissolve in the hot AC, but rather the aromatic oils of the AC are absorbed into the dense polymer chains of the rubber, causing the CRM particles to swell and become tacky (6). A fully reacted particle swells 3 to 5 times its original size (24). This "reaction" is analogous to a dry compressed sponge being placed in water. As the sponge absorbs water, it swells and softens. As the CRM particles absorb oil, they soften, expand and cause the binder viscosity to increase and eventually stabilize when the reaction is complete. Viscosity increases during the reaction not only as a result of the CRM particles growing, but also because the AC loses its lighter oils through absorption in the rubber. Reaction time with the McDonald technology is generally 30-60 minutes, depending on the blending temperature. If the CRM used is finer than normally used with the McDonald process, it is believed the required reaction time and temperature can be lowered. Rouse Rubber Industries states the time required for CRM to fully react is a direct function of the CRM's relative surface area. They promote using their UltraFine CRM for its ability to decrease a combination of blending temperature and/or blending time (25).

Storability

If the temperature remains hot enough for an extended period past the reaction time, the AR viscosity will begin to decrease. This is a result of the CRM depolymerizing and melting in the asphalt. Chehovits reports (6) that ARs derived from CRM generally hold their physical properties for up to 24 hours, if the storage temperature does not exceed 175°C (348°F). He states depolymerization occurs within 3 to 6 hours if the storage temperature approaches 200°C (392°F). Takallou

states this depolymerization occurs much earlier, around two hours, at normal blending temperatures (17).

Depolymerization concerns prevent users from storing AR for extended periods, resulting in increased mix production costs for several reasons. First, the specialized blending equipment must be at the mix plant requiring transportation and set up costs. Second, an unexpected shutdown from the plant or jobsite may mean the AR has to be discarded. Another contributor to cost is that production of the AR may not be fast enough to keep pace with the desired mix production rate.

Proprietary products are available which claim to produce storable AR, possibly eliminating the need for on-site blending units. This would allow the binder to be blended at refineries or asphalt terminals like conventional ACs, with no modification needed at the mix plant. FLEXOCHAPE (17, 26) and ECOFLEX (27) are two such products. Both use 10% CRM by weight of AC. They have been used sparsely in the United States (28), possibly because their license fees may offset the advantage of storability.

Compatibility

For a reaction to fully occur which improves binder characteristics, compatibility between the CRM and AC must exist. Compatibility is governed by the chemical composition of both the CRM and the AC, although other factors may also limit the reaction, such as blending temperature and relative surface area (particle size and texture) of the CRM. Compatibility is normally demonstrated when the CRM is blended into the AC and the viscosity rises to a certain level and stabilizes within about one hour. If the hydrocarbon content in the CRM is high, more of the CRM particle will actually swell, making it more compatible (6). However, it is believed most of the CRM produced today from scrap tires has a relatively

homogenous blend of different rubber polymers, making compatibility more a matter of AC composition than CRM composition (4). The AC chemical composition can vary greatly depending on crude source. Asphalt is composed of varying amounts of asphaltenes (solids), aromatics (oils), and saturates (gels). During the reaction, the aromatics are absorbed by the CRM. If the crude source is low on aromatics, compatibility problems are likely because of insufficient aromatics for the CRM to absorb. There is also concern that if few aromatics remain, cold temperature flexibility will be severely decreased. An extender oil is often added to provide the required aromatics.

Improved Binder Properties

AR is believed to be less sensitive to temperature than conventional AC, thereby improving HMA performance (6). A higher relative stiffness at high operating temperatures is desired along with a lower relative stiffness at low operating temperatures. High temperature stiffness is increased by the presence of the reacted CRM, while a decrease in low temperature stiffness is often obtained by the use of a lower viscosity base cement or adding an extender oil. With the McDonald technology, the AC selected is typically one or two viscosity grades lower than the standard AC used for that region. Along with stiffness, other empirical and physical properties have been evaluated to determine the difference between AR and conventional AC, such as softening resistance, penetration, elasticity, flexibility, and ductility (24, 29, 30, 60). Generally, results show improved high temperature properties with the added CRM. Low temperature improvements are not as consistently shown, but can be obtained with the combination of a softer AC and CRM. Testing variance on AR is often higher than on conventional AC, possibly due to inconsistent concentrations or mixing of CRM in the AC.

PERFORMANCE CLAIMS ON CRM MIXES

The rubber industry has made claims that CRM will improve almost all aspects of mix performance. This biased viewpoint is clearly evident when one compares literature written or sponsored by rubber producers (32, 33) to those written independently (3, 4, 34). This is not to imply all these claims are untrue, but rather to emphasize that the reader should be aware of an author's background and interests. Listed below are the "claimed" improvements of adding CRM to HMA with both the wet and dry processes. Some of these claims are not based on proven field performance or even lab testing, but mere speculation.

Wet Process

Claims of improved mix performance with binder modified by the wet process are based on the improved binder properties. As the high temperature binder stiffness increases by the presence of CRM, the mix stiffness is also thought to increase, thereby offering *greater deformation resistance*. This relationship between binder and mix stiffness was characterized by Van der Poel, Huekelom and Klomp (35, 36). Increasing mix stiffness by stiffening the binder at high operating temperatures is generally believed to reduce rutting (37). However, most literature states that lab mix stability (generally done at 60°C) will generally be lower when using AR versus a conventional AC, because the optimum binder content is generally higher with AR (4, 7, 8). This challenges the claim that using AR will reduce deformation potential by increasing mix stability. In addition, several recent field studies have shown rutting to be more a function of the mineral aggregate character (angularity and gradation) and the percentage of voids filled with binder, rather than of binder stiffness (38, 39).

AR is also claimed to *reduce fatigue cracking*, which results from repeated loading. With the addition of rubber, the elasticity of the binder is claimed to increase which should allow the mix to better resist the repeated tensile stresses caused from repeated wheel loads. One recent study, funded by an AR producer, showed rubberized HMA withstanding 5 to 20 times more load repetitions before failure than conventional HMA (40). One should be aware that with fatigue testing, the relative performance of the mixes is greatly influenced by whether samples are tested at constant stress or at constant strain, and whether the log cycles to failure were plotted versus log applied stress or versus log applied strain. A shift factor must also be used to relate lab fatigue testing to field performance.

Less thermal cracking is believed to result if the AR is more flexible (less stiff) at low operating temperatures. Kennedy's estimate is that thermal cracking is influenced 88% by the binder and only 12% by other mix properties (41). If the softer grade cement selected for CRM modification can retain its low temperature properties while having its high temperature stiffness increased enough to resist deformation, the mix should better resist thermal tensile strains. *Less reflective cracking* from underlying pavement crack movement is claimed with mixes of the wet process because the AR is believed to be more elastic than conventional AC, withstanding greater strain before failure (42).

Since higher optimum binder contents are typical of AR mixes, *better aging properties* can be expected because of the thicker binder films. The antioxidants and carbon black from tire rubber are also believed to reduce aging. Rubber producers also claim that *reduced design thicknesses* can be used for a new or overlay pavement if a CRM mix is selected. California is the first and only state to modify their overlay design procedures, allowing for reduced thicknesses by as much as a half if a specific gap-graded AR mix is used (43).

Dry Process

The performance benefits claimed of the dry process are based on two phenomena. The first is how the larger CRM particles act as a flexible substitute to the aggregate they replaced. The second phenomenon is binder modification may occur with the addition of the finer CRM particles. Since any binder enhancements would parallel those discussed with the wet process, only the claimed effects of "rubberized aggregate" are discussed here. These effects should be combined with the benefits derived from any binder modification to explain the full effect of adding CRM by the dry process.

Ice debonding and improved skid resistance normally occur with PlusRide because the surface has exposed rubber particles which compress when loaded (44, 45). A thin layer of ice forming on these particles will debond as traffic rolls across. In wet conditions, the friction between the tire and the road surface is believed to improve because of the exposed rubber particles. *Less reflective and thermal cracking* may result if the rubber aggregate can absorb the stress when the tip of the crack reaches the CRM particle (46). *Less fatigue cracking* may occur if the elastic rubber aggregate can absorb and release energy as the pavement flexes under repeated loads (44, 47). *Better rutting resistance* of RUMAC has been demonstrated in one study due to added resiliency (47), although this claim has been refuted in other studies (46).

WET PROCESS MIX DESIGNS

General Considerations

Standard Marshall and Hveem mix design procedures have been used to design dense-graded HMA using AR. Adding CRM generally raises optimum binder content and lowers lab stability with either mix design system. This is because the AR has a higher viscosity relative to conventional AC, preventing close packing of

the aggregate and therefore requiring more binder for the same VTM. This in turn lowers Marshall and Hveem stability. When using an AR binder, the aggregate gradation selected often will have higher voids in the mineral aggregate (VMA). This "opening of the gradation" of a dense-graded AR mix is to make room for the swelled CRM particles. If these soft, fully reacted and swollen particles are making contact with the aggregate, compaction could be a problem (7, 8).

Open and gap-graded mixes with AR can be designed with normal methods. Both typically require higher optimum binder contents than a dense-graded mix. Draindown of the hot AC from the aggregate after mixing can be a problem with open and gap-graded mixes unless a binder stabilizing agent of some sort is used. By using AR with its higher viscosity, the hot binder draindown should be less, allowing for a thicker binder film. The AR viscosity is affected not only by the AC grade and mixing temperature, but also by the amount and compatibility of the CRM. Generally, a higher CRM content and a more compatible CRM will increase viscosity. A finer gradation of CRM has been found to quicken the reaction and subsequent undesired depolymerization, if temperatures stay high long enough. However, finer CRM gradation has not been conclusively found to affect viscosity more than coarser gradations (6).

McDonald Technology

McDonald AR is used for a variety of pavement material applications other than as a HMA binder. It was first used in 1964 as a hand-placed surface repair. The first utilization of AR in a stress absorbing membrane was in 1967 and then in a stress absorbing membrane interlayer in 1971. Asphalt Rubber was first used as crack sealer in 1974 and in HMA in 1975. All of these first trials were performed in the state of Arizona and used AR blends from two similar technologies, ARCO

and Sahuaro, which later merged in 1983-85 and became known as the McDonald technology (20).

The McDonald method of blending was patented until 1993, when it became nonproprietary. Fifteen to 22% (by weight of binder) ground CRM is used with a typical maximum size of 16M (1.2 mm). This CRM gradation is not uniform, but rather has particle sizes ranging from 16M down to 200M (1.2-.075 mm). The gradation requirements are finer for dense-graded mixes than for open-graded because there is more VMA in open-graded mixes for the CRM to reside without causing compaction problems.

Continuous Blending Technology

One of the biggest drawbacks with the McDonald technology is the AR is produced in batches with a reaction time of 30 minutes to one hour, which can lead to production delays at the mix plant. A relatively new non-proprietary continuous blending method can eliminate the batch process. It was developed by Rouse Rubber Industries and first used in Florida in 1989 (13, 48). Florida calls this process the *Florida generic wet* process, while others call it the *Rouse continuous blending* method. Compared to the McDonald method, it uses less CRM and a finer CRM gradation. Special self-contained equipment manufactured by Rouse is used to blend an AC-5 or AC-10 asphalt with 5 to 15% (by weight) of finely ground CRM, with a maximum size of 40 to 80M (.42-.20 mm). This fine gradation allows for a faster reaction and lower temperature blending, allowing the AR to be utilized at the plant more like a conventional binder.

DRY PROCESS MIX DESIGNS

General Considerations

RUMAC has typically been designed using the Marshall or Hveem methods, but the criteria for selecting the optimum AC content is different than typically used with these methods (4, 10). Lab stability values of RUMAC are significantly lower than of conventional mixes, and flow values are much higher. Experience has shown the critical parameter for RUMAC is the VTM, generally with an allowable range of 2 to 4%, and a design target of 3%. This is roughly 1% lower than for conventional mix designs. Since a gap-graded aggregate is often used to make room for the CRM particles, the lower VTM values are achieved by increasing both the AC content and the amount of mineral filler.

PlusRide

The first dry process technology was developed in Sweden in 1960 and licensed in the United States in 1978 under the tradename PlusRide. The mix design was refined in the mid 1980's to the present day proprietary PlusRide system (49). PlusRide typically utilizes 3% CRM (by weight of mix) mixed directly into the heated aggregate prior to the addition of the binder.

Both the required aggregate and CRM gradation bands of PlusRide are very narrow. There are three different PlusRide aggregate gradations which can be chosen, each based on a different maximum aggregate size. There is only one CRM gradation used for all three aggregate gradations. All three aggregate gradations are gapped between the $\frac{3}{4}$ -inch and 10 mesh sieves, allowing room for the CRM. The majority of CRM is granulated and passes the $\frac{3}{4}$ -inch (6.3 mm) sieve. The combination of aggregate and CRM is thought to produce a dense-graded mix (4). Because the majority of CRM has a large relative size and smooth surface, it is

believed to act as a flexible aggregate and have little influence on the binder. However, 18 to 24% of the CRM passes the 20 mesh sieve, and this finer fraction of CRM is believed by some to partially react with the binder. A soft asphalt/rubber interface is created between the CRM and AC, helping bond the two materials together.

The cost of PlusRide has been 50 to 100% higher than conventional HMA (4, 5). This is due to the narrow gap-grading of the aggregate and the CRM, a typically higher binder content and the required royalty fee. Binder content is generally 2% higher than a conventional mix using the same type aggregate. The AC grade normally selected for PlusRide is typically the same as for conventional mixes in the region. Target VTM is between 2 to 4% (7).

TAK System (Original Generic Dry)

The first form of a generic dry system, called the TAK system, was developed in 1986 by Takallou (9, 10, 17). Although similar to PlusRide, the TAK system differs in a few ways. Rather than using a fixed CRM and aggregate gradation like PlusRide, the TAK system selects the CRM gradation based on the aggregate gradation to be used. A standard dense-graded aggregate gradation is chosen and the CRM gradation is adjusted based on where the rubber particles can fit. Swelling of CRM particles after contacting the AC is considered when the CRM gradation is selected (7). Normally 1 to 3% CRM (by weight of mix) is used, which is less than PlusRide. A combination of granulated and ground CRM is used, which is sized much finer than PlusRide. The granulated CRM larger than 10M, which is roughly half, is designed to function as rubber aggregate, while the granulated and ground CRM finer than 10M, consisting of the other half, is intended to modify the binder. Since the CRM with the TAK system is finer than with PlusRide, more binder

modification is expected. A pre-treatment of the CRM with a catalyst can be used to achieve a pre-swelling of the CRM particles. According to Takallou, this helps achieve an optimum reaction (17).

The 75-blow Marshall hammer mix design method is generally used. Optimum AC content is selected based normally on 3% VTM, although 2 to 4% is allowed. Modified criteria for stability and flow are also established. The literature of this public-domain system is not very specific with regards to mix design procedures, and Takallou has often been hired as a consultant.

New Generic Dry System

Another dry process technology, probably derived from the TAK system, adds strictly 16 to 80 mesh ground CRM. This is referred to as the "new generic dry system" in this dissertation. With only fine CRM, the goal is not so much to rubberize the aggregate but to modify the binder. Typically less than 1.5% CRM (by weight of mix) is used with this technology. Four states (Oklahoma, Arkansas, Kansas, and Iowa) have tried this new system at least once since 1993, but Kansas has the most experience (16). Kansas was using the continuous blending wet method with UltraFine CRM (80M), but decided to try adding the same CRM by the dry method. It worked well and they have continued building test sections with this system. The cost to rubberize HMA with the dry process versus the wet process, assuming the same size and amount of CRM is used, is about one-third (5).

In Kansas, crushed limestone is the predominant HMA aggregate and is used with this new generic dry system. Trial lab specimens are prepared in accordance with standard Marshall methods, with the CRM added to the dry aggregate in the mixing bowl. The amount of CRM is based on weight of either the mix or AC. The AC is heated to a slightly higher temperature (10 to 30°C) than required to produce

the standard mixing viscosity, prior to mixing with the hot aggregate and CRM. Optimum AC content is selected based on air voids.

CONSTRUCTION OF CRM MIXES

Mixing, laydown and compaction temperatures are higher for both wet and dry CRM mixes, relative to conventional mixes. They are mixed between 145 to 175 °C (293 ° to 347 °F), placed hotter than 135 °C (275 °F), and compacted as soon as possible before the mat cools. Compaction as soon as possible is required because the AR viscosity increases rapidly when the temperature drops, making compaction difficult. To prevent pickup problems, detergent-based release solutions are used on steel drum rollers, truck beds and laydown equipment. Petroleum-based solutions cannot be used as the mix will stick to the equipment. Pneumatic rubber tire rollers cannot be used because of pickup problems. Blotter sand is often used prior to trafficking the new sticky surface to prevent pickup. With RUMAC, compaction may have to continue longer than normal because the larger CRM particles may react and expand under the elevated temperatures. Additional rolling helps maintain mat density until the binder cools and gains strength to counteract the expansion tendencies of the partially or non-reacted CRM (4, 10).

FIELD PERFORMANCE HIGHLIGHTS

There is a wide range of opinions on the merits of using CRM in HMA because field trial results have varied widely from state to state. Different environmental conditions cause some of this variance, but there are also many different mix design, production and construction variables associated with the different technologies. The numerous combinations of these variables in field applications has provided many successes, as well as many failures. There is also not

a long history of performance with CRM mixes relative to the use of other additives. It is beyond this chapter's scope to attempt to objectively summarize the field performance of all projects using CRM mixes. However, a few performance highlights will be mentioned of the five specific CRM design technologies discussed earlier.

McDonald

A 1992 survey showed roughly twice as many projects have used the wet process versus the dry, and the McDonald technology has been used five times as often as any other wet process technology (2). Two states, Arizona and California, have the most experience with McDonald AR as an HMA binder. Since 1987, Arizona has been utilized two different HMA designs using AR. The first is an open-graded friction course mix placed with a 1-inch thickness. The second is a dense-graded surface course mix placed with a 1½ to 2-inch thickness. Both are used over either rigid or flexible pavements. The friction course utilizes approximately 8% binder while the dense-graded mix uses approximately 6% binder. Both use an AR of 20% CRM and 80% AC-10 asphalt. Arizona's increased use of these mixes indicates they are relatively satisfied with their performance (50).

California also has had positive experiences with McDonald AR. Its use in HMA began in 1978 and it has been used on 24 overlay projects in California through 1992. On the early projects, equal thicknesses were used for both the CRM and conventional HMA. Since better performance from the AR mixes was consistently evident, reduced thicknesses were tried starting in 1983. California has concluded that reduced overlay thicknesses of a specific AR gap-graded HMA, called ARHM-GG, will equal or outperform conventional HMA by exhibiting less distresses and needing less maintenance. They believe a longer fatigue life will result from the

mix being able to tolerate higher deflections, and slower oxidation will occur due to the mix's lower permeability. They have observed reflective cracking is mitigated longer, and cracks, once visible, progress at a slower rate (52, 59). In February 1992, California became the first and only state to issue guidelines which allow overlay thicknesses to be reduced when using CRM HMA. A 50% reduction in thickness is allowed in California when ARHM-GG is used (43).

Continuous Blending Technology

Rouse Rubber Industries reported, by the end of 1993, nine states had used the continuous wet blending technology with their UltraFine CRM, of either 40M or 80M nominal maximum size (25). Five other states have used this UltraFine CRM to produce AR for HMA, but with a relatively fast batch process versus the Rouse continuous blending equipment. There appears to be no difference with the actual AR produced from these two methods, only a difference in how it is produced. Florida was the first to use this UltraFine CRM in 1989, and by 1994 had fully implemented its use in all surface mixes for state and federal roads. Two standard designs are used for surface mixes in Florida, a dense-graded mix and an open-graded friction course mix. The dense-graded mix uses 80M CRM at only 5% by weight of binder, while the open-graded mix uses 40M CRM at a concentration of 12% by weight of binder. The open-graded mix has more space for the larger size and higher concentration of CRM to fit without interfering with the aggregate structure. Even though the dense-graded mix has only 5% CRM, Florida believes the binder's elasticity is improved which should reduce rutting (13, 48, 51).

PlusRide

15 states have experimented with PlusRide, but Alaska is the only one with extensive experience in using this RUMAC product (28). Several other states' initial trials with PlusRide have failed due to premature raveling (3). Even Alaska was disappointed with its initial test sections built in 1979, but has since concluded the benefits of ice-debonding and improved skid resistance in their state can be worth the 50 to 100% increase in cost (44). PlusRide is a very sensitive mix with regards to variations in gradation and binder content, as well as placement and compaction procedures (28). This may partially explain some states' unsuccessful initial trials with PlusRide, and then Alaska's eventual success, once they acquired the necessary experience.

TAK System

The state of New York and the Canadian province of Ontario have had relative success on several demonstration projects using this method, although New York did experience some raveling problems (14, 15). New York has since adopted and issued design specifications for using CRM, based on the TAK system.

New Generic Dry System

From 1990 to 1992, Kansas built four projects using this method, each with many test sections. UltraFine 80M CRM was used, at rates varying from 5 to 12.5% by weight of binder or from .5 to 1.5% by weight of aggregate. Dense-graded and gap-graded mixes were used predominantly with an AC-10. Iowa had a one-mile resurfacing project in 1993 with this system using 50M CRM at a rate of 10% by weight of binder. Arkansas and Oklahoma had larger projects in 1994 with this

system, using the UltraFine 80M CRM at rates of 1.5% and 1.0% by weight of aggregate respectively.

All of these except the last Kansas project used double-drum mix plants, requiring little operational change at the plant compared to a conventional mix. The bulk CRM was blown from a truck into a mineral filler silo. It was then metered and conveyed into the outside drum of the mixing chamber, immediately after the AC. The last Kansas project used a single-drum mixer, where the CRM was blown into a coater at the discharge end of the drum. There is concern that if the CRM is introduced close to the dryer flame in a drum, the CRM may blow out. No significant mixing or construction problems were encountered on any of these projects.

A pugmill mixer was used with this system by Florida in 1989 for a very small test section. The UltraFine CRM was added to the aggregate in the pugmill prior to the AC being introduced (53). No problems were encountered.

Discussions with Kansas DOT personnel concerning field performance of their CRM test sections indicate the CRM, added wet or dry, has not significantly inhibited the reflection of cracks in the dense-graded mixes. The gap-graded CRM mixes, however, both with the wet and dry process, have mitigated reflective cracking more than the conventional mixes. Kansas DOT personnel noted that with the gap-graded mixes, the CRM prevented the AC from draining off the aggregate, allowing a thicker AC film and hopefully better durability. Also noted was the similarity to a gap-graded mix design called Stone Mastic Asphalt (SMA) where fibers, instead of CRM, are used to prevent drain-down (16).

CHAPTER III. TEST PLAN

This chapter covers the test plan and the rationale for its design. After a brief discussion of how the specific objectives were chosen, the development of a general plan to achieve these objectives is explained. Tables and flowcharts are then presented which quickly describe the test plans for Phase I and Phase II. A rather detailed discussion then follows on the specifics of the plan along with the rationale used for their selection. First, the AC and CRM material is covered, followed by the preparation procedures used to produce the binder blends tested in Phase I and the AR utilized in Phase II. Next, the constant CRM/AC ratio used in both phases is discussed. The aggregate and its gradation for Phase II are then examined. Next, various mix design elements used in Phase II are covered to include; design criteria, compaction, short-term aging, mixing/compaction temperatures, wet and dry mixing procedures, and specific gravities of the various mix components. Finally, the rationale for selecting the characterization tests used in both phases is examined.

FOCUS ON A SPECIFIC OBJECTIVE

As discussed in the previous chapter, there were many variables dealing with the performance of CRM mixes. One aspect of CRM technology to which little attention had been given, but which appeared to offer significant opportunity for cost savings, was adding the finely ground CRM by the dry rather than the wet process. The literature discussing the dry process systems, especially those which use the finer CRM, continually referred to a "partial" or "possible" binder modification which may

occur, but no one had attempted to quantify it. This specific gap in the technology became the focus of this research effort. The primary objective is to compare the performance effects of the wet process and the dry process when adding the same CRM to the HMA. Two secondary objectives can be accomplished concurrently under the one test plan and tie directly into the primary objective. Secondary objective #1 involves using the SUPERPAVE binder tests to characterize the effects of adding CRM both in a reacted and unreacted state. Secondary objective #2 examines the effects of changing the size of ground CRM for both the dry and wet processes.

DEVELOPMENT OF A GENERAL PLAN

Developing the test plan was somewhat an iterative process as tests were performed and modifications made to the plan based on cumulative test results. It was especially desirable to utilize the new state-of-the-art SUPERPAVE binder test equipment in the test plan, since the tests are applicable for modified as well as unmodified binders and were developed to be performance-based. Assuming the CRM is fine enough and the mixture's VMA is adequate, the effects of adding finely ground CRM with the wet or dry process should be limited to binder modification, rather than rubberization of the aggregate. Given this, binder tests should be more sensitive than mix tests at characterizing these effects. It was felt an optimum test plan would include the SUPERPAVE binder testing followed and complimented by mix testing.

The primary objective calls for a comparison of properties from samples prepared with the wet process and the dry process. For mix testing, both processes could be accurately simulated in the laboratory using established mixing procedures. For the SUPERPAVE binder testing, the wet process could be simulated in the

laboratory simply by testing the fully reacted AR. The challenge occurs when trying to simulate the dry process and it's "partially" or "possibly" reacted CRM/AC blend for binder testing.

After exploring several possibilities, it was determined that accurate modelling of any reaction taking place in the dry process with binder tests was impossible. Extraction methods from mix samples using the dry process were considered, but several obstacles made any testing meaningless. First, the CRM would be filtered out with the fines during extraction, leaving only the base AC in an altered form, with many of the light ends absorbed by the CRM. Secondly, the CRM properties would likely change by coming in contact with the solvent used for extraction (54). Another option of simulating the dry process for binder tests was attempted under this effort by quickly mixing the CRM in the AC at lower than normal reaction temperatures, and then rapidly pouring the CRM/AC blend into the Thin Film Oven (TFO) pans for short-term aging. No lengthy mechanical agitation occurred, as is typical when reacting the CRM and AC. It was discovered early, however, that an almost complete reaction occurs in the TFO, and significant reaction occurs as well during long-term aging in the Pressure Aging Vessel (PAV). These data will be presented later in Chapter V. This preliminary finding demonstrated extended agitation was not necessarily needed for a reaction to occur, and the TFO environment (163 °C for 5 hrs) as well the PAV environment (100 °C @ 300 psi for 20 hrs) were adequate for some reaction to occur.

Although the partial reaction of the dry process is impossible to model for binder tests, there is still a way to examine the range of expected performance for the dry process blend by determining both extremes of the reaction spectrum. Worst case scenario is no reaction, and the CRM acts only as a rubberized inert filler. As this research was being conducted, no one had yet examined how unreacted CRM

modified the binder. For testing, blend samples had to be prepared with unreacted CRM, achieved with this research by the procedure described later in this chapter. Best case scenario, which few believe occurs, is a full reaction. These samples had to be taken from fully reacted AR. By testing both extreme ends of the reaction spectrum, the respective performance levels of each extreme are established. There is also a need to know where the control (no CRM) binders rate relative to the performance of unreacted and fully reacted CRM blends. This approach of establishing both possible extremes of the dry process performance spectrum is used for Phase I of the test plan, which consists of the SUPERPAVE binder tests. Phase II involves only mix testing, where it is believed the dry process as well as the wet process can be modeled correctly in the lab.

PHASE I TEST PLAN OUTLINE

The ten primary binder blends tested in Phase I are described in Table 3.1. They are grouped as four fully reacted AR blends, four unreacted "CRM/AC-10" blends, and two control viscosity graded asphalt cements with no CRM. More information on the AC and CRM selected, as well as how both the reacted and unreacted blends were prepared, is given later in this chapter.

Table 3.2 provides the sequence of the SUPERPAVE tests with relation to the aging of the binder, the temperatures the tests were run at, the number of sample repetitions performed, and the distress mode each test is known to examine. The rationale used for selecting these test specifics is provided later in this chapter. The tests are described in the next chapter.

The sequence of blending, aging and testing of the 10 primary blends for Phase I is flowcharted for convenience in Figure 3.1. Once the reacted blends (AR) were prepared, they were aged and tested like the control blends. Test samples were

prepared after the blend had been appropriately aged. For the unreacted blends, the flowchart shows how the base AC-10 was appropriately aged prior to the CRM being added. The CRM was quickly but thoroughly mixed into the AC-10 and the samples immediately poured. Reaction was limited by minimizing the temperature and time the CRM and AC were in contact with each other.

Table 3.1 Phase I Primary Binder Blends Tested

| Group Description | Specific Blend Labels |
|---|---|
| - Controls (no CRM) | AC-10 AC-30 |
| - CRM (15%) blended with AC-10 and FULLY reacted | 16M-R (reacted) 40M-R " 50M-R " 120M-R " |
| - CRM (15%) blended with AC-10 but NOT allowed to react | 16M-U (unreacted) 40M-U " 50M-U " 120M-U " |
| 10 total blends tested | |

Table 3.2 Phase I Test Information

| Sequence | Test Name | Age of Sample | Testing Temp., °C | Sample Reps. | Distress Mode Examined |
|----------|-----------|------------------------|-------------------|--------------|------------------------|
| 1 | DSR | Original (before TFO) | 58, 64, 70, 76 | 2 | Tenderness |
| 2 | DSR | Short-term (after TFO) | 58, 64, 70, 76 | 2 | Rutting |
| 3 | DSR | Long-term (after PAV) | 10, 16, 22, 28 | 2 | Fatigue |
| 4 | BBR | Long-term (after PAV) | -18 | 3 | Cold-temp. cracking |
| 5 | DTT | Long-term (after PAV) | -18 | 12 | Cold-temp. cracking |

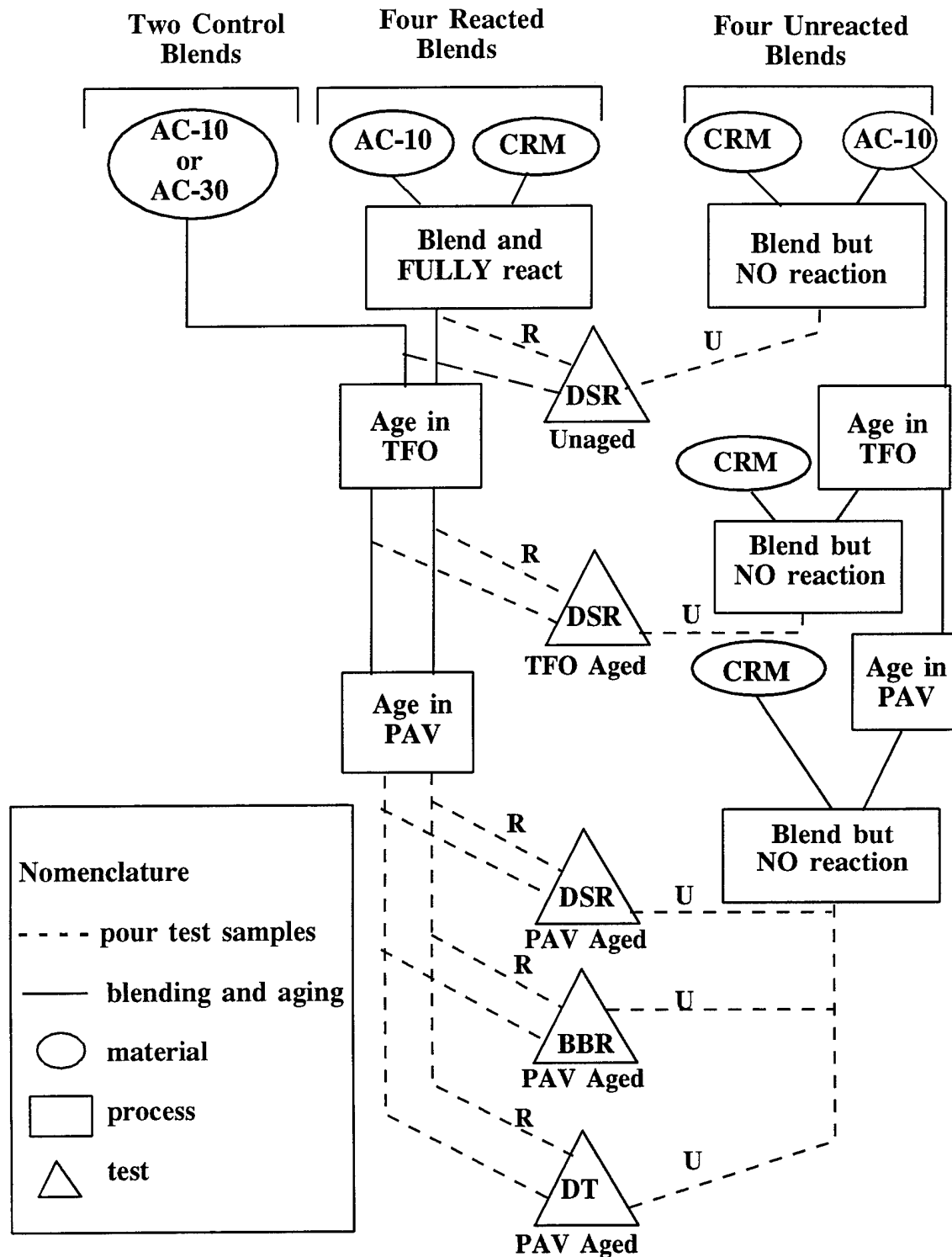


Figure 3.1 Flowchart of Blending, Aging and Testing, Phase I

Along with the 10 *primary* blends listed in Table 3.1, five *supplemental* blends were prepared which received limited testing. Table 3.3 describes and labels each of these supplemental blends, and lists the testing which was performed on each. These supplemental blends are listed separately because the complete series of Phase I tests were not performed on them. Their purpose was to help determine how much reaction occurs from the TFO Aging Test and from the PAV Aging Test.

Table 3.3 Supplemental Binder Blends Which Had Limited Testing

| Group Description | Label | Testing Performed |
|---|---|--|
| - CRM mixed with original AC-10 just prior to blend being aged in TFO, and then later in PAV. Reaction may occur in TFO and/or PAV. | 50M-TFO | DSR after TFO, DSR after PAV, BBR after PAV, and DT after PAV |
| - CRM mixed with short-term aged AC-10 just prior to blend being aged in PAV. Reaction may occur in PAV. | 16M-PAV 40M-PAV 50M-PAV 120M-PAV | DSR after PAV |

PHASE II TEST PLAN OUTLINE

The five mixes tested in Phase II are described in Table 3.4. They are grouped as: two mixes utilizing the wet process, two utilizing the dry process, and a control with no CRM. More information about the AC, CRM and aggregate used follow in this chapter.

Highlights of the mix design and sample preparation procedures used in Phase II are listed in Table 3.5. A more thorough discussion of these items, along with the rationale for using them, also follow in this chapter.

The tests selected for phase II are described in Table 3.6 along with the distress mode they examine. The abbreviation listed for each test is used in the following Figure 3.2, which is a flowchart of Phase II testing. This flowchart applies to each of the five mixes, and indicates which tests were run on which sample category (same mix, aging, and VTM%), along with the number of sample repetitions. Note that an indirect tensile strength (ITS) had to be obtained for each sample category prior to the resilient modulus (RM) testing. This is because all the RM tests were run and/or corrected to 15% of the ITS. This will be explained further in the next chapter when the RM test is described.

Table 3.4 Phase II Mixes Tested

| Group Description | Specific Mix Labels |
|---|---------------------|
| CONTROL - AC-30 added to aggregate (no CRM) | CNTRL |
| WET PROCESS - CRM and AC-10 fully reacted (AR), then mixed with aggregate | 16M Wet 80M Wet |
| DRY PROCESS - CRM added to aggregate, then AC-10 mixed in | 16M Dry 80M Dry |
| 5 total mixes | |

Table 3.5 Phase II Mix Design and Sample Preparation Highlights

| | |
|-------------------------|---|
| general procedure | - individual designs performed for each of the 5 mixes - 3 samples made for each of 4 (or 5) trial binder %'s |
| design criteria | - optimum binder content selected based on 4% VTM |
| compactor | - SUPERPAVE gyratory, 106 gyrations |
| sample size | - 100 mm diameter by 60 mm high |
| aggregate | - 100% limestone, gap-graded, 12.7 cm ($\frac{1}{2}$ -inch) maximum particle size |
| CRM/AC-10 ratio | - constant at .15 for both wet <u>and</u> dry samples |
| volumetric calculations | - CRM was considered as part of the binder for both wet <u>and</u> dry samples |
| mixing temp. | - target 163 °C (325 °F) |
| mixing time | - 2 to 2½ minutes |
| aging of loose mix | - 4 hrs at 152 °C (306 °F) |
| compaction temp. | - target 149 °C (300 °F) |
| test samples | - all prepared at optimum binder %, except for some creep test samples (see Figure 3.2) - 4% VTM samples obtained with full 106 gyrations - 7% VTM samples obtained with less gyrations |

Table 3.6 Phase II Test Information

| Test Abbrev. | Test Description | Distress Mode Examined |
|--------------|--|----------------------------|
| IT | - Indirect Tensile Test at 25 °C to determine failure ϵ | Cracking |
| RM | - Resilient Modulus Test at 5, 25, and 40 °C, and at 15% of indirect tensile strength (ITS) | Temperature susceptibility |
| Creep | - Dynamic Creep Test at 60 °C, 138 kPa confining σ , and 827 kPa axial σ | Rutting |
| LT Age | - Long-term aging of 7% VTM samples at 85 °C for 5 days. Compare RM values before and after aging. | Aging |

FOR EACH OF THE 5 MIXES

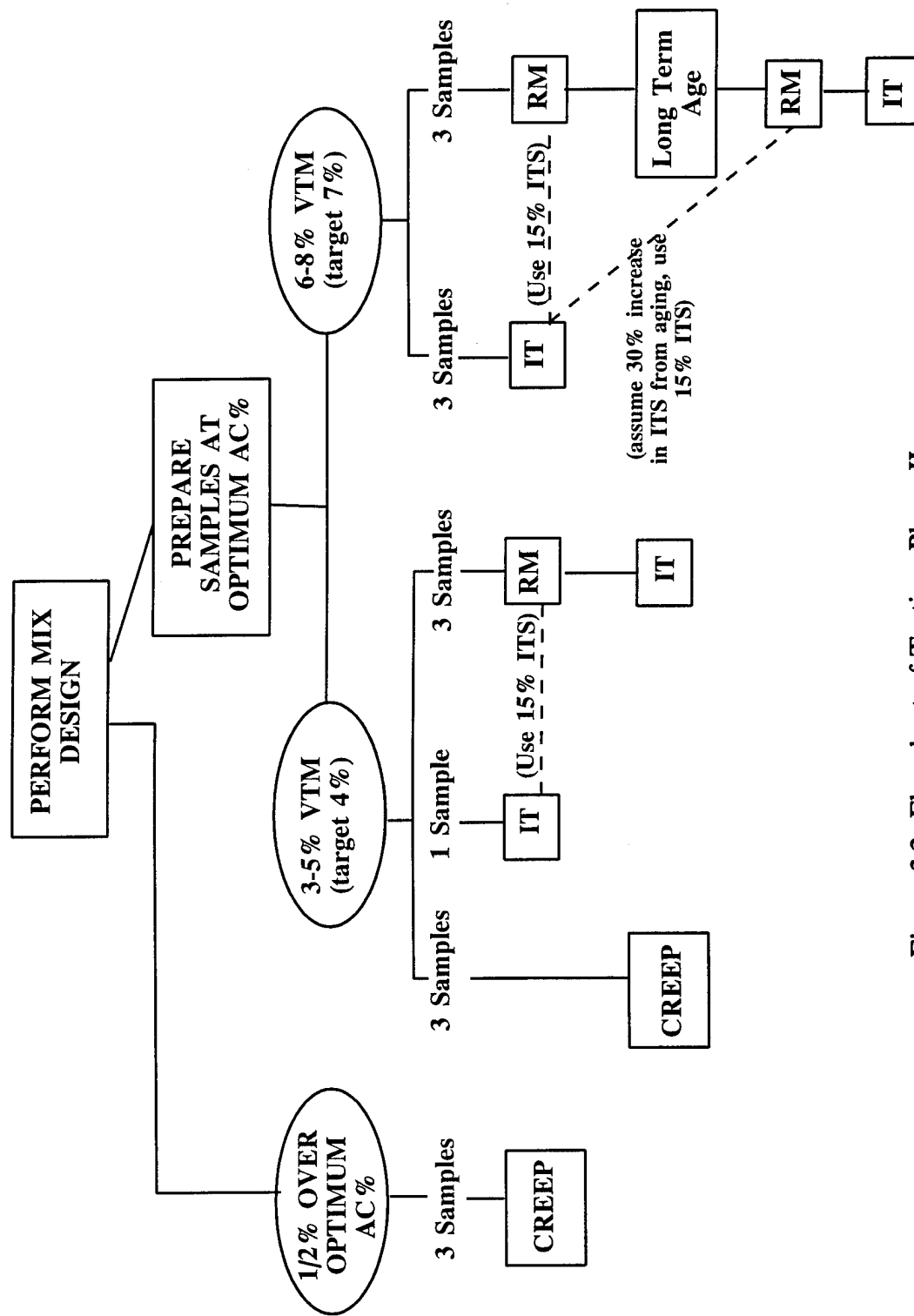


Figure 3.2 Flowchart of Testing, Phase II

SELECTION OF SPECIFICS AND RATIONALE

Asphalt Cement

The AC source selected was the Lion Oil Co. refinery in El Dorado, Arkansas. This source was known to provide AC's which had a sufficient aromatic oils to allow for a complete reaction with the CRM, making it "compatible" with the CRM.

An AC-10 grade was selected as the base AC for blending of both the reacted and unreacted CRM binders, as well as the wet and dry mix samples. This is a typical grade when 10 to 20% CRM is added wet, although AC-5s and AC-20s have also been used. AC-10s have also been used with the new generic dry system, specifically in Kansas. Other states have used higher grades with the dry process, but since direct comparisons are made between the wet and the dry, the AC grade needed to be the same. The AC-10 was also used as a control in Phase I.

An AC-30 grade was selected for the control mix in Phase II. This is a typical grade used in the southeastern United States if CRM is not added, and states typically drop one or two grades when 10 to 20% CRM is added wet. A two grade difference was chosen (versus one) because the AC-30 had high temperature viscosities closer to those of the CRM/AC-10 blends than the AC-20. The AC-30 was also chosen as a second control for the binder tests to aid in understanding the relative significance of the effects of adding CRM to the AC-10. For instance, the addition of unreacted CRM to the AC-10 may increase the rutting parameter by a certain amount, but it would help to understand the relative significance by comparing to an AC-30 as well.

Conventional test and SUPERPAVE properties of the AC-10 and AC-30 are included in Appendix A. The SHRP performance grade (58) for the AC-10 was a PG58-28 while for the AC-30 was a PG64-22.

CRM

Rouse Rubber Industries in Vicksburg, Mississippi was chosen as the source of the ground CRM to be used. They are one of the largest producers of ground CRM and have been the exclusive producer for states using the new generic dry system with 40M and finer CRM. A CRM chemical analysis provided by Rouse is included in Appendix A.

Four ground CRM gradations, 16M, 40M, 80M and 120M nominal maximum size, were originally chosen for testing. It seemed probable that the dry process mixes would experience more reaction as the CRM became finer. In addition, secondary objective #2 is to examine the effects of different CRM sizes to both binder and mix properties.

The 16M was the largest CRM size selected because of the desire to minimize any particulate effects during the binder testing as well as to minimize any interference the CRM may have with the aggregate during compaction. Although 80M is the finest CRM normally used in HMA, 120M was included in phase I to research the effects of using even finer CRM.

A labeling error by the producer on one of the CRM bags resulted in the supposedly 80M really being about a 50M nominal maximum size. This was not discovered until after the binder testing was complete. Thus, the four actual CRM sizes used for binder testing were 16M, 40M, 50M, and 120M nominal maximum size. Two CRM sizes were used in Phase II, 16M and a true 80M (taken from a new CRM bag). These two are pictured in Figure 3.3 to display their size and texture. A series of sieve analyses for all five sizes used in this project is summarized in Table 3.7. Means and standard deviations of the percentage passing each sieve size is listed. Six samples of the 16M and 40M were analyzed while two samples of the 50M, 80M and 120M were analyzed. Since the CRM used in this project came

running a Rota-Tap Screen Shaker for 30 minutes. These modifications were recommended by Rouse Industries (25).

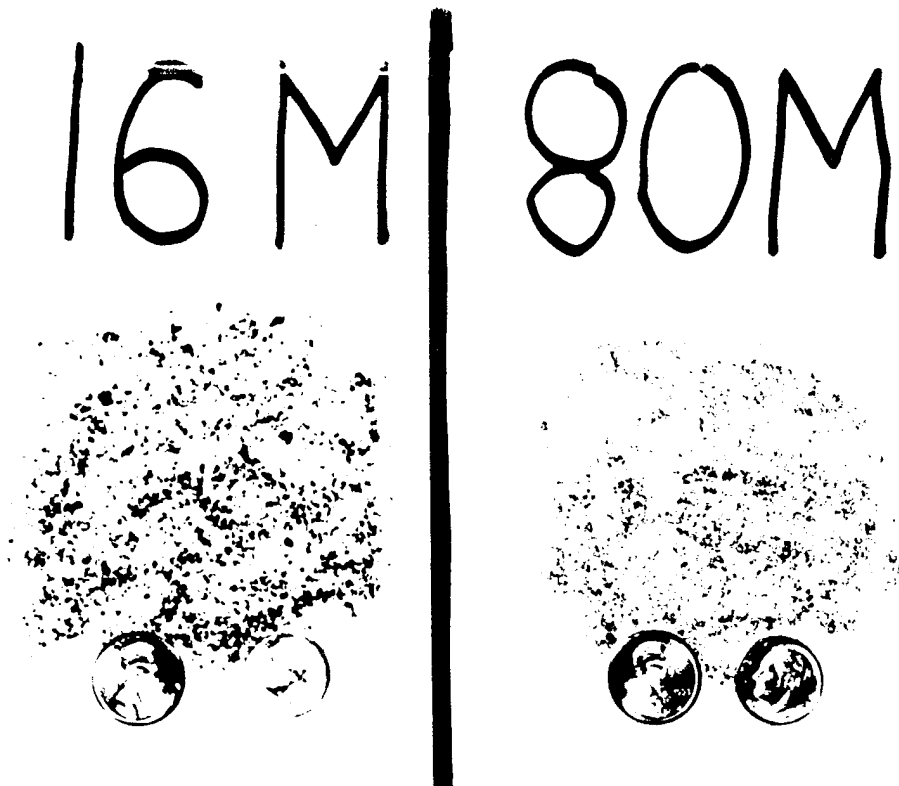


Figure 3.3 Photo of 16M and 80M CRM

Table 3.7 Sieve Analysis of CRM Used

| Sieve Size | % CRM Passing | | | | |
|---|---|---|---|---|--|
| | Average (avg) \pm Standard Deviation (σ) | | | | |
| | 16M CRM (6 reps) avg $\pm \sigma$ | 40M CRM (6 reps) avg $\pm \sigma$ | 50M CRM (2 reps) avg $\pm \sigma$ | 80M CRM (2 reps) avg $\pm \sigma$ | 120M CRM (2 reps) avg $\pm \sigma$ |
| #10 | 100 \pm 0 | | | | |
| #16 | 95.7 \pm 0.6 | | | | |
| #20 | * 87.7 | 100 \pm 0 | | | |
| #30 | 58.2 \pm 2.1 | | 100 \pm 0 | | |
| #40 | * 38.8 | 90.9 \pm 0.5 | 93.2 \pm 0.3 | | |
| #60 | | | | 100 \pm 0 | |
| #80 | 6.3 \pm 0.4 | 20.7 \pm 0.5 | 25.3 \pm 0.4 | 92.2 \pm 0.4 | |
| #100 | # 2.8 \pm 0.3 | 13.2 \pm 0.4 | 17.5 \pm 0.5 | 79.9 \pm 0.5 | 100 \pm 0 |
| #120 | | 9.0 \pm 0.3 | 13.6 \pm 1.0 | 66.3 \pm 0.4 | 99.3 \pm 0.3 |
| #140 | | | | 48.4 \pm 0.2 | 84.0 \pm 0.6 |
| #200 | | 2.2 \pm 0.2 | 4.1 \pm 0.4 | 22.6 \pm 0.1 | 47.9 \pm 1.1 |
| Footnotes: * - means only one 16M rep (versus 6) at this sieve size # - means only five 16M reps (versus 6) at this sieve size | | | | | |

Preparation of Binder Blends and AR

The unreacted blends for Phase I were prepared by minimizing the time and temperature at which the CRM was in contact with the AC-10. The correct amount of CRM was added to the appropriately aged AC-10, quickly mixed by hand with a spatula, then immediately poured as samples and cooled. The temperature of the AC-10 was only hot enough to allow for thorough mixing and pouring, never getting above 135°C (275°F). Only small quantities of the blend were mixed at a time, which also minimized the contact time between the CRM and hot AC-10. Another

factor inhibiting any reaction in some cases was that the aromatic oils in the AC-10, which react with the CRM, were partially burned off during TFO and PAV aging.

The reacted blends tested in Phase I and the AR used in the "wet" mixes of Phase II were prepared using procedures established by Rouse Rubber Industries (25) and NCAT. These are outlined in Appendix A. Basically, the AC-10 was heated to 177°C (350°F) in a one-gallon pour-pot and then the appropriate amount of CRM mixed in. The blend was periodically stirred and remained at 177°C throughout the reaction period. The Brookfield viscometer (spindle #3 at 20 rpm) was used to measure the viscosity at various times during the reaction period. Procedures for taking these viscosity measurements are also included in Appendix A. The modification was considered complete when the viscosity leveled off, typically between 40 and 60 minutes. The temperature was then lowered. Figure A.1 in Appendix A shows the viscosity measurements plotted versus time during the reaction period for the four reacted blends of phase I and one AR of phase II. These reaction curves are not smooth, even though the procedure followed ensured the spindle had been rotating a constant duration when the readings were taken. The expected trend of a faster reaction occurring with the finer CRM was not evident, although the data were limited since reaction time was not part of this study.

All blends in Phase I, including the controls, were only heated high enough during sample preparation to allow for adequate pouring without air pockets. This was aided by mildly heating the sample molds prior to pouring.

CRM/AC-10 Ratio

A constant CRM/AC-10 ratio of .15, or 15% CRM by weight of AC, was chosen for all samples in Phase I and Phase II. With the wet process, the range used by states has been roughly 5 to 25% with 10 to 20% most common. Thus, 15%

appeared to be a good representative ratio to use for the wet process. With the new generic dry system, the range of CRM used has been roughly .5 to 1.5% by weight of mix, with 1% being common. Although it depends on the optimum binder content, the amount of CRM for "1% by weight of mix" approximates that for "15% by weight of AC." In fact, an optimum binder content of 6.7% will allow the two to each have the same weight of CRM. 6.7% is a reasonable value to expect for optimum, so the CRM/AC-10 ratio of .15 was expected to provide a representative CRM concentration for mixes in the field using the new generic dry system. As it turned out, the optimums from the five mix designs were lower than this, due to the VMA being lower than expected. Still, the amount of CRM in the dry mixes fell within the range used in the field.

The choice was made with the dry process mixes to maintain a constant CRM/AC ratio (like the wet process) versus a constant CRM/aggregate ratio. A constant CRM/aggregate ratio would have been more consistent with field practices, but also would have been estimated to try to provide the same amount of CRM as used in the corresponding "wet" samples. This would have only been an estimate because the optimums of the "dry" mixes were unknown. With the primary objective in mind, it was felt a constant CRM/AC ratio could provide a more meaningful comparison between the binder modification which occurs with the dry process versus that with the wet process. This choice meant the CRM in the dry process mixes should be considered part of the binder during volumetric and mix design calculations, which also matches the wet process mixes.

Aggregate and Gradation

A 100% crushed limestone from a local quarry was used in Phase II. A non-absorptive aggregate (like limestone) was desired to maximize availability of light

ends of the AC for reaction with the CRM in the dry process. It was felt a better comparison could be made between the binder and mix results with a non-absorptive aggregate. Kansas uses a majority of limestone in their CRM mixes, with either process. Using a small portion of natural sand was considered, but the gap-gradation desired would have closed quickly. The Kansas AR surface mix specification limits the amount of natural sand to a maximum of 10%, while their AR base mix is limited to no more than 15%. Thus, the decision to use no natural sand was made.

A gap-gradation was chosen for several reasons. First, a gap-graded mix will typically have more VMA than a dense-graded mix, which was desirable to minimize CRM interference during compaction. Second, avoiding any bridging of the CRM with the aggregate particles, which can occur with a dense-graded mix, was desired. These bridging effects may have been reflected in the test results, which would have blurred the binder modification effects. Lastly, three states [Arizona (55), California, and Kansas] are now typically using gap-gradations for their CRM mixes because they believe performance is better than dense-gradations.

The specific aggregate gradation for this project was selected to simulate both the Kansas and California rubberized gap-graded mix specifications. The limits of both gradations are plotted in Figure 3.4 and the gradation chosen which satisfied both states' specification. It was decided to stay on the fine side of the California gradation because of possible draindown problems, especially with the control mix. The selected gradation also meets the suggested gradations for gap-graded HMA with AR given in the FHWA regional workshop notes (8). In addition, the SUPERPAVE gradation criteria was met, as well as the SUPERPAVE minimum VMA limit and the SUPERPAVE voids filled with asphalt (VFA) range (56).

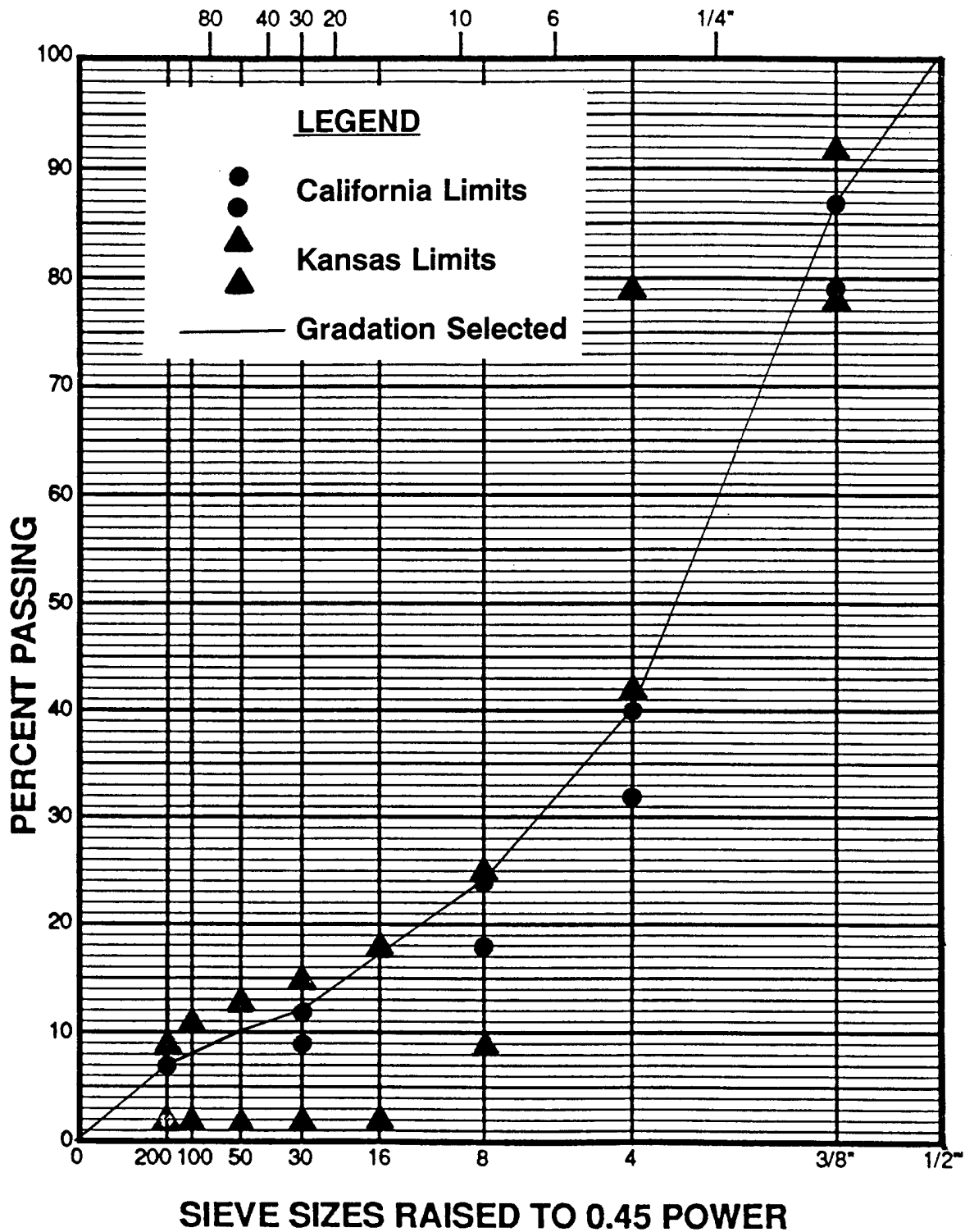


Figure 3.4 Gap-Gradation Selected Compared to Kansas and California Gap-graded Specification Limits

The target gradation shown in Figure 3.4 was acquired fairly easily by batching from nine individual sieve sizes during sample preparation. This also provided gradation consistency. Four random batches were checked to determine actual gradation. The average and standard deviation of percentage passing values from these checks are shown in Table 3.8. Because of dust on the aggregate, the actual gradation was slightly finer than the target gradation.

Table 3.8 Actual Aggregate Gradation Used

| Sieve Size | $\frac{1}{2}$ " | $\frac{3}{8}$ " | No. 4 | No. 8 | No. 16 | No. 30 | No. 50 | No. 100 | No. 200 |
|----------------------------|-----------------|-----------------|-------|-------|--------|--------|--------|---------|---------|
| Average % Passing (4 reps) | 100 | 88.7 | 42.9 | 24.5 | 18.6 | 13.0 | 10.7 | 8.8 | 7.6 |
| Standard Deviation | 0.0 | 0.2 | 0.7 | 0.0 | 0.2 | 0.2 | 0.1 | 0.2 | 0.1 |

Mix Design Elements

When the Phase II test plan was developed, the SUPERPAVE mix design procedures were not finalized. However, many of the more important aspects were established. Thus, it was decided to use as many of the SUPERPAVE procedures as practical. The SUPERPAVE mix design procedure (56) is based on 4% VTM. Thus, 4% VTM was chosen as the mix design criteria. Individual mix designs were performed for each of the 5 mixes to select the optimum binder content. Each design involved 4 or 5 trial binder contents, at which 3 samples were prepared. After a design was complete, test samples were prepared at the selected optimum binder content. The results of the mix designs will be discussed

in Chapter VI, and will include the specific gravities of the mix and its components.

A SUPERPAVE gyratory-shear compactor prototype was selected for sample compaction. Several SHRP studies (57) showed gyratory compactors simulated field compaction better than other compactor types, ie, impact, kneading and static pressure. The standard SUPERPAVE gyratory compactor parameters of a 1.25° angle, 600 kPa (87.5 psi) vertical pressure, and a rate of 30 gyrations/minute were used. These were checked several times during the project to ensure they were not changing. Aggregate batches of 1150 grams (2.536 lb) produced 100 mm (3.93 in) diameter mix samples approximately 60 mm (2.4 in) high. The required number of gyrations in the SUPERPAVE mix design procedure is based on the traffic expected during the pavement's design life. SUPERPAVE criteria (56) requires 106 gyrations for 3 to 10 million Equivalent Single Axle Loads, which is a representative estimate of traffic for an average interstate highway over 10 to 20 years. The 4% VTM samples (3-5% was the acceptable range) were compacted with the full 106 gyrations, while the 7% VTM samples were compacted by a reduced number of gyrations to produce VTM in the 6-8% acceptable range. This number varied, but generally was around 50 gyrations.

Also included in SUPERPAVE procedures is short-term aging of the loose HMA immediately after mixing and prior to compaction. At the time this plan was being developed, SUPERPAVE procedures called for 4 hours of aging at 135°C (275°F), with the mix placed on a flat pan in an oven and stirred every hour. Phase II did include 4 hours of short-term aging, but with a few modifications. Metal batch cans, 13 cm high by 10 cm in diameter, were used to hold the loose mix and then covered with aluminum foil. There were two reasons

for this change. First, it was thought the pan requirement may change, since it required a large amount of oven space and stirring time. A 10 x 9 inch pan would be necessary for each sample to meet SUPERPAVE criteria. Second, it was felt the cans did a better job simulating the environment of a storage silo and/or haul truck. Simulating this field environment the most accurate way possible was critical to this research, since any binder reaction of the dry process likely occurs during this short-term aging. With this in mind, the aging temperature was also changed to 152°C (306°F) because of the typically higher mixing (and thus storage) temperatures used with both the wet and dry processes. The mixes were not stirred, ensuring a consistent temperature by keeping the oven closed.

Along with storage temperature, mixing and compaction temperatures were selected based on a review of the literature. It was preferred to use the same temperatures for the wet, dry, and control mixes (if consistent with field practices) to eliminate any additional variables. A target mixing temperature of 163°C (325°F) was selected. Due to the aggregate and binder cooling slightly in the mixing bowl, they were heated to 165°C (330°F) prior to mixing. This provided a binder viscosity in the recommended mixing range for the AC-30 and AR blends (wet process), but was too hot for the AC-10 used in the dry process. It was still felt important to maintain the same temperatures for the wet and dry mix designs. In addition, the binder viscosity likely increased when the AC-10 met the dry CRM in the aggregate of the dry mixes. The target compaction temperature was 149°C (300°F), allowing time for the mix to be removed directly from the short-term aging oven at 152°C and briefly remixed by hand with a spatula in a bowl for 10 seconds. The mix was then transferred to the heated (149°C) gyratory mold for compaction. Little draindown was noted in the cans for any of the mixes prepared at optimum binder content.

The wet process mixing procedures were similar to those of a conventional mix, except the binder was fully reacted AR rather than conventional AC. The dry process mixing procedures were slightly different. The CRM was considered part of the binder for mix design and mix volumetric calculations. The correct amounts of CRM and AC-10 to be added in each sample batch had to first be calculated by solving two equations simultaneously for each trial binder content:

$$Wt_{\text{binder}} = Wt_{\text{AC-10}} + Wt_{\text{CRM}} \quad \text{and}$$

$$0.15 \times Wt_{\text{AC-10}} = Wt_{\text{CRM}}$$

where:

$$\begin{aligned} Wt_{\text{binder}} &= \text{weight of binder} \\ Wt_{\text{AC-10}} &= \text{weight of AC-10} \\ Wt_{\text{CRM}} &= \text{weight of CRM} \end{aligned}$$

The CRM was weighed in small pen tins and added to the hot aggregate in the mixing bowl. The CRM-aggregate mixtures were briefly hand-mixed with a spatula prior to adding the AC-10 and mixing. Mixing time was 2 to 2.5 minutes for all 5 mixes.

Phase I Binder Tests

All the SUPERPAVE performance-related binder tests were used to characterize the 10 treatments. DSR tests were first run on unaged, short-term aged and long-term aged specimens to evaluate tenderness, rutting and fatigue, respectively. BBR and DTT tests followed on long-term aged specimens to evaluate cold temperature cracking. The SUPERPAVE binder test procedures were fairly well established when Phase I testing began, although final standards were not yet published (58). Any deviations from these "now final standards" will be noted here or in the next chapter.

One deviation from SUPERPAVE standard procedures was the short-term aging. The TFO Test, per AASHTO T179, had to be used versus the Rolling

TFO (RTFO) Test, per AASHTO T240, because the AR would lump and crawl out of the RTFO bottles. This problem had been encountered by others trying to age AR in the RTFO, and their solution was to use the TFO. Long-term aging was with the PAV per AASHTO PP1 (58).

Test temperatures were chosen which were thought to produce measured parameter values in the proximity of the SUPERPAVE binder specification pass/fail criteria values per AASHTO MP1 (58). If these pass/fail values were met within the range of testing temperatures, then the exact temperature at which the criteria would be met could be determined and compared to the other binder blends. This is similar to the SUPERPAVE binder grading protocol. Temperatures remained the same for all 10 treatments to be able to make direct comparisons. Four DSR test temperatures, 58, 64, 70 and 76 °C, were chosen to test the unaged and short-term aged samples for tenderness and rutting, respectively. Temperatures of 10, 16, 22 and 28 °C were chosen for DSR tests on long-term aged samples for fatigue. A test temperature of -18 °C was chosen for the BBR and DTT. Only one temperature was used because, unlike the DSR test, single samples cannot be retested at different temperatures. It was felt repetition at the same temperature was more important than testing at different temperatures.

The number of test sample repetitions for each of the three types of tests were selected based on the test's repeatability, which was only generally known at the time. Since the DSR seemed very repeatable, it was decided to test only two samples (meaning two sample repetitions). The BBR seemed slightly less repeatable, so three sample repetitions were believed needed. The DTT appeared extremely variable, so 12 samples were tested.

Phase II Mix Tests

Several factors were considered when selecting mix tests. Tests were desired which could identify differences in how the AC/CRM blends affected the five mixes, especially differences between the wet and dry processes. It was desired to examine as many of the pavement failure modes as possible, especially those related to the *enhanced performance claims* of CRM mixes due to binder modification, discussed in Chapter II. Obviously, tests which NCAT was equipped for and were industry standards were preferred.

The indirect tensile (IT) test was chosen because its strain at failure (ϵ_f) is considered to be an indicator of *cracking* potential (53). Resilient modulus (RM) testing was done at 5, 25 and 40 °C (41, 77, 104 °F) to try to assess *temperature susceptibility*. RM at 25 °C is currently required in the AASHTO structural design guide (61). The dynamic confining creep test, run at 60 °C (140 °F), was selected because it is believed to be a good evaluator of *rutting* (60). In addition to testing 4% VTM samples (at optimum binder content), three samples per mix prepared for the mix design at approximately ½% over optimum were creep tested. *Aging susceptibility* was examined by comparing RM measured on samples before and after long-term aging. Preliminary SUPERPAVE aging procedures were used. This procedure requires aging of samples prepared at 7% VTM (6-8% allowed) in a force draft oven at 85 °C for 5 days. Samples are turned and moved to different positions in the oven each day. The higher VTM is intended to increase the rate of aging. All mix testing was performed with three sample repetitions for each category.

CHAPTER IV. TEST DESCRIPTIONS

This chapter provides a brief description of each characterization test and their measured parameters. Many of the testing specifics were covered in the previous chapter regarding the test plan. The focus here will be explaining the physical properties each test measures and their relation to expected performance. The DSR, BBR and DTT tests of Phase I will be discussed first followed by the IT, RM and Creep tests of Phase II. Procedures will be referenced to a testing standard except for deviations, which will be noted.

PHASE I

DSR

The DSR is an oscillatory torsional loading system using concentric rotational loading on a binder specimen sheared between parallel plates. The thin specimen is sandwiched between two circular plates which are either 25 mm or 8 mm in diameter. The plates and sample are maintained at a constant temperature, within .1°C, by a water bath connected to a thermal control unit. The entire test is controlled by computer.

Testing followed standard test method AASHTO TP5 (58). The tests were run with a constant strain mode, frequency of 1.5 Hz, and temperatures shown in Chapter III. As per standard, the 25 mm plate was used for original and short-term aged testing while the 8 mm plate was used for long-term aged testing. A deviation from standards was using a 2 mm gap (meaning a 2 mm thick specimen) rather than

the standard 1 mm gap on the 8 rubberized blends for the original and short-term aged testing. The standard 1mm gap was used for the two control blends with the original and short-term aged testing. All long-term aged blends used the standard 2 mm gap. This gap increase was necessary to minimize the particulate effects of the CRM. Researchers have suggested keeping the particles smaller than $\frac{1}{4}$ to $\frac{1}{2}$ the gap size. The 16M CRM had a *maximum* particle size of 1.2 mm, although its *average* particle size was much smaller. The gap was not set greater than 2 mm because the blends may flow out from between the plates at the higher temperatures. The gap size will not change the measured properties as long as the input data during test setup is correct. This was verified in the lab.

Two fundamental material properties measured with the DSR are the complex shear modulus (G^*) and the phase angle (delta or δ). G^* is a measure of binder stiffness and is computed as the absolute shear stress divided by the absolute shear strain. A higher G^* means a stiffer binder and greater resistance to deformation under load. Delta is a measure of relative elasticity, or said another way, how much the binder will recover from deformation once unloaded. Delta is computed as the lag in the stress response compared to the applied strain. A totally elastic sample will have no lag between stress and strain, with $\delta = 0^\circ$. A totally viscous sample will have a $\frac{1}{4}$ cycle, or $\delta = 90^\circ$, stress lag behind the applied strain. This lag is an indicator of energy lost in viscous deformation relative to the energy stored for elastic recovery. The more elastic a binder is, the more resistant it will be to viscous flow and non-recoverable shear strain, resulting in better performance (63).

SUPERPAVE parameters to measure tenderness, rutting and fatigue performance use a combination of G^* and δ . For tenderness and rutting, the parameter $G^*/\sin\delta$ is used, where a larger value represents better performance. For

fatigue, the parameter $G^*(\sin\delta)$ is used, where a smaller value is desired. With both parameters, a more elastic binder (smaller δ) reflects better performance.

BBR

The BBR is a creep test to characterize cold-temperature cracking potential of a binder. It applies a constant 100 gm point load at the midspan of a beam sample and continuously measures the beams midpoint deflection for a duration of 4 minutes. The beam is 127 mm long, 12.7 mm wide, 6.3 mm thick and is simply supported at both ends by steel half-rounds spaced 102 mm apart. The beam, poured from long-term aged binder, is submerged in a fluid bath to control the low temperature within .2°C and provide a buoyant force to counteract the beam's weight. The entire test is controlled by computer. Tests were in accordance with AASHTO TP1 (58).

SUPERPAVE performance criteria uses two parameters from this test: the creep stiffness (S) and the logarithmic creep rate (m), both measured at the 60 second point during the test. The S value is a ratio of maximum bending stress in the beam divided by the maximum bending strain. The m value is the absolute of the slope of the log S versus log time curve. A smaller S and larger m represents better cold-temperature cracking properties.

DTT

The DTT measures the cold-temperature strain and stress at failure in a binder specimen pulled at a constant elongation rate of 1.0 mm/min. The test specimen, shaped as a dogbone, is prepared with long-term aged binder. It has a minimum cross section of 6 x 6 mm where it should fail. Two plastic inserts grip the binder during the test and transfer the direct tensile load from the machine to the specimen. The test is performed at cold temperatures where the binder exhibits

brittle, versus ductile, behavior. A non-contact extensometer is used to measure the specimen's elongation during the test. Tests were in accordance with AASHTO TP3 (58).

SUPERPAVE criteria use the tensile strain of the specimen when the load reaches a maximum, reported as ϵ_f . A larger ϵ_f value indicates the binder can sustain more elongation before cracking, thereby improving its cold-temperature performance.

PHASE II

IT

Two testing standards were partially used for the IT test. ASTM D 4867-88 uses the IT test to determine moisture susceptibility while ASTM D 4123-82 (RM test) describes the load orientation and narrow loading strips used in the IT test. In the test, a compressive line load is applied diametrically to a cylindrical specimen. The result is a uniform tensile stress over most of the plane defined by the diameter and length of specimen. Specimens crack along the loaded diameter at failure. This stress and strain at failure, called ITS and ϵ_f respectively, are calculated by assuming the mix is homogeneous, isotropic and elastic. A Marshall loading machine was used which applies a progressive load at a rate of 2 inches/min. The sample temperature of 25°C was maintained by air, rather than a water bath as ASTM D 4867-88 dictates. The ϵ_f value is used as an indicator of a mix's ability to resist cracking.

RM

The RM is a fundamental engineering property which characterizes how the HMA strains under stress and is thus used in pavement design and analysis. A repeated load is applied to a specimen and the displacements are measured. The

RM is calculated as the ratio of stress to recoverable (resilient) strain under repeated, square wave loading conditions.

Test procedures followed ASTM D 4123-82. The loading arrangement is similar to the IT test, so the same assumptions and calculations are used to determine stress and strain. The primary difference is the RM test applies a smaller cyclic load and does not fail the specimen. The load is applied for 0.1 seconds and unloaded for 0.9 seconds before repeating itself. The horizontal elongation of the specimen's diameter is measured with each loading cycle to calculate the RM.

This test was used to determine any difference between the mix's temperature susceptibility by measuring RM at 5, 25, and 40 °C and then performing regression analysis. In addition, relative differences between the mixes were analyzed at each temperature.

Hot Mix Asphalt is not a totally linear elastic material and thus, the amount of stress applied will affect the RM value measured. Because of this, the RM tests were run and/or corrected to applied tensile stresses of 15% of the ITS for each sample category and temperature (ASTM allows a range of applied tensile stresses between 10 to 50%). The ITS at 25 °C for each sample category was first determined by an IT test. The ITS at 5 °C was assumed to be 3 times greater than the ITS at 25 °C while the ITS at 40 °C was assumed to be 7.5 times less than the ITS at 5 °C. This established NCAT procedure is based on the relationship between ITS and temperature (31). RM tests of all sample categories were run at the same time, first at 25 °C, then at 5 °C, and finally at 40 °C. It was not always possible to load to stresses equal to 15% ITS, so RM values were normalized to 15% ITS stress conditions. Correction factors of 0.04226/°C at 40 °C and 0.02380/°C at 25 °C were used while no correction was used for the 5 °C RM tests. These factors were established by NCAT (31). The larger correction factors are needed at the higher

temperatures because the samples behave in a more viscous manner when hot (rather than elastic). A sample tested at 12% ITS at 40 °C would be corrected to 15% ITS stress conditions by decreasing its measured RM value by 12.7% ($12-15 \times 0.04226\%$). Conversely, a sample tested at 17% ITS at 25 °C would be corrected to 15% ITS stress conditions by increasing its measured RM value by 4.8% ($17-15 \times 0.02380\%$).

Creep

NCAT's dynamic confining creep test procedure was used. The specimens are tested at 60 °C (140 °F) temperature with 138 kPa (20 psi) confining pressure and 827 kPa (120 psi) axial stress. The specimen is wrapped by a rubber membrane and then placed into a confining pressure vessel. This vessel is placed in an environmental chamber in preparation for loading. After the temperature has stabilized, a small conditioning load is applied. The test begins by applying axial impulse loads of 827 kPa for a .1 second duration, with a .9 second relax time. The load applications run for 60 minutes, or 3600 cycles. A computer controller records the axial strain with time. Results of the creep testing under this research are reported as simply the percentage permanent strain of the sample after the 60 minutes of cyclic loading. The sample heights for the permanent strain calculation are measured immediately before and immediately after the 60 minute load period. Stable mixtures generally have permanent strains no higher than 5% with this test configuration (62). Another parameter that was measured was the "% rebound" axial strain of the sample during the 15 minute relaxation period immediately following the 60 minute loading period.

CHAPTER V. PHASE I TEST RESULTS AND ANALYSIS

This chapter is divided into two main sections to present and analyze the results of Phase I. The first section covers DSR testing. Relationships of G^* versus (vs) temperature, δ vs temperature, and δ vs G^* are shown for the 10 primary blends to determine relative stiffness, elasticity and temperature susceptibility. Next, the tenderness, rutting and fatigue parameters are plotted vs temperature. The extreme temperatures at which the SUPERPAVE criteria are barely met for each blend are tabulated for a better perspective of the blends' predicted performance differences. An analysis of the effect of CRM gradation follows. Finally, the TFO aging ratios of the control and reacted blends are presented to determine which age faster. The second main section covers the BBR and DTT testing. The average S , m , and ϵ_f values of each blend are first presented to determine relative cold temperature expected performance. The S and m values are then plotted vs temperature to tabulate the minimum temperature at which the SUPERPAVE criteria is still met.

All of the individual sample test results for both Phases are tabulated in the Appendices, allowing for further analysis if desired. Appendix B covers the DSR test results and Appendix C the BBR and DTT test results. A brief explanation of the tables is provided at the beginning of each appendix.

For ease of reading the many figures in this chapter, the legends were made consistent. The AC-10 and AC-30 control blends are always identified by solid lines

with squares and triangles as data points respectively. The reacted (R) blends are always represented by dotted lines, and the unreacted (U) blends by dashed lines.

DSR TESTING

G^* , δ , and Temperature Relationships

Figure 5.1 is a plot of the \log_{10} average G^* vs temperature for the reacted and unreacted 16M blends (16M-R and 16M-U), as well as the AC-10 and AC-30. Both the "after TFO" series of tests (58, 64, 70 and 76 °C) and the "after PAV" series of tests (10, 16, 22 and 28 °C) are presented on the same plot. Each series of data points are joined by lines for convenience of reading. Figure 5.2 is a similar plot with the same blends from the same tests, but with δ , rather than G^* , plotted on the y-axis vs temperature. The trends for these two types of plots, which will be discussed below, are generally the same for all four CRM sizes. Thus, for the sake of brevity, G^* and δ are plotted on dual y-axes in Figures 5.3, 5.4 and 5.5 for the 40M, 50M and 120M blends, respectively. The R and U blends for each CRM size are shown along with the same AC-10 and AC-30 data. It is important to remember when viewing these plots that the CRM blends have the AC-10 blend as their base AC.

Any differences which can be seen on the log scale between the average G^* data points are generally statistically significant because of the extremely small variance of G^* within the two sample repetitions. This small variance of G^* is demonstrated by the following statistics. The overall (for all ten primary blends) average CV of G^* within the two sample repetitions was calculated as only 2.64% for the TFO tests and 5.35% for the PAV tests. These values were calculated in Appendix B and then noted on Figure 5.1, although they apply to Figures 5.3 through 5.5 as well. The overall average CV of G^* , and later of δ , $G^*/\sin \delta$, and $G^*(\sin \delta)$,

was reported in lieu of the standard deviation. The reason is that the variance, and thus standard deviation, of G^* was proportional to G^* 's magnitude, which varied by a factor of 10 over the 18°C testing range. CV measures variability proportional to the mean.

The overall average CV of δ was only 0.27% for the TFO tests and 0.88% for the PAV tests, as calculated in Appendix B and noted on Figure 5.2. These low variances apply to Figures 5.3 through 5.5 as well.

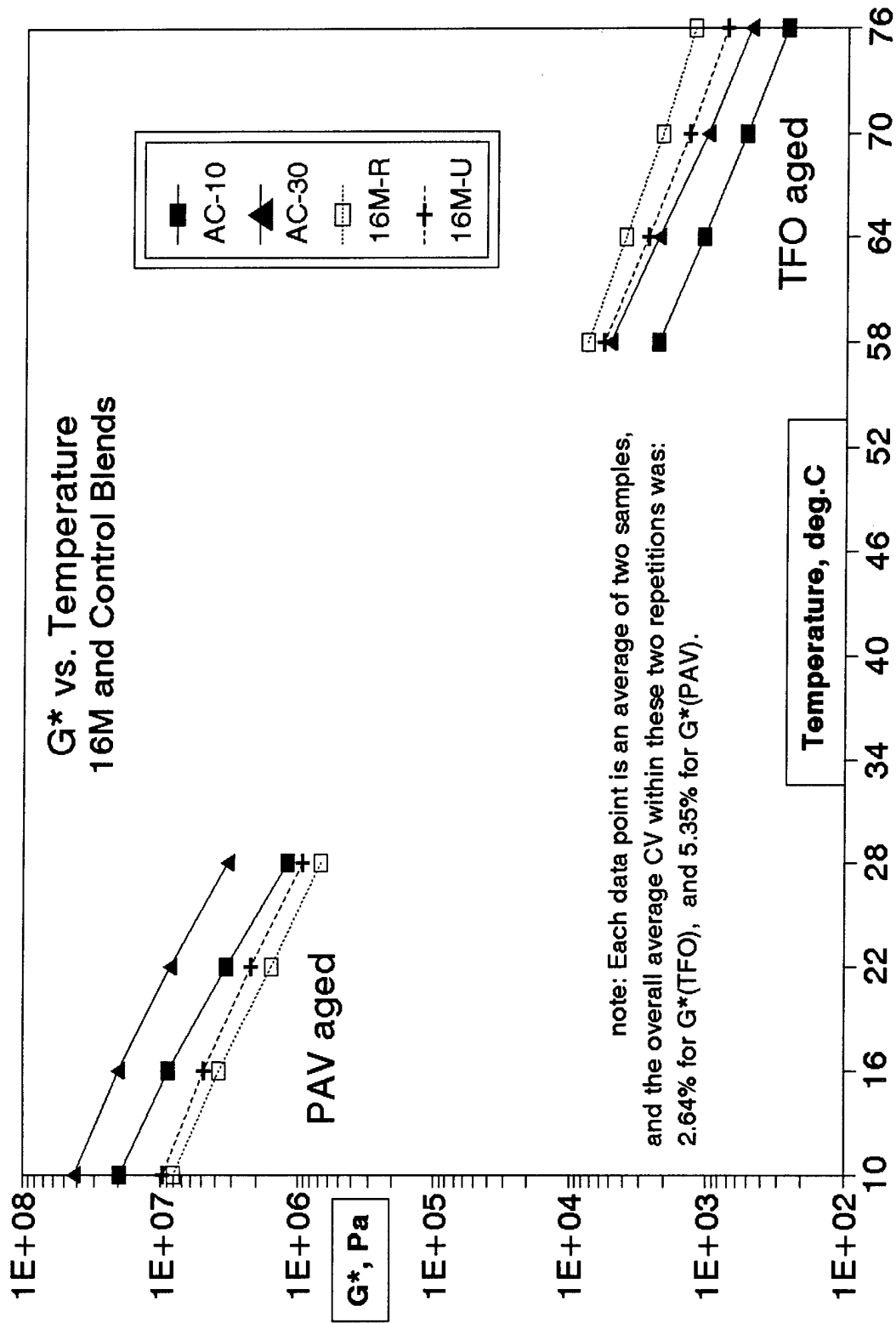
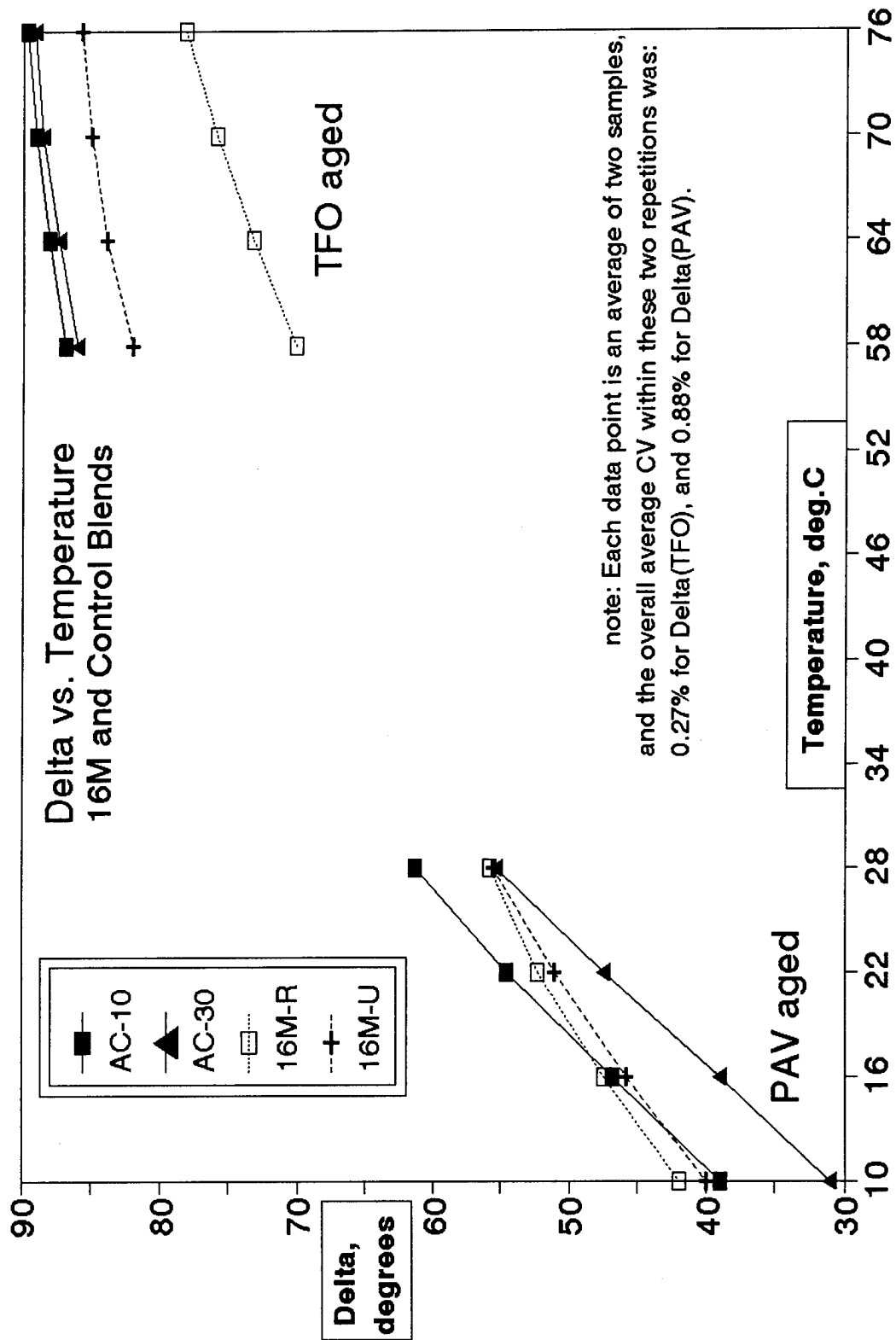
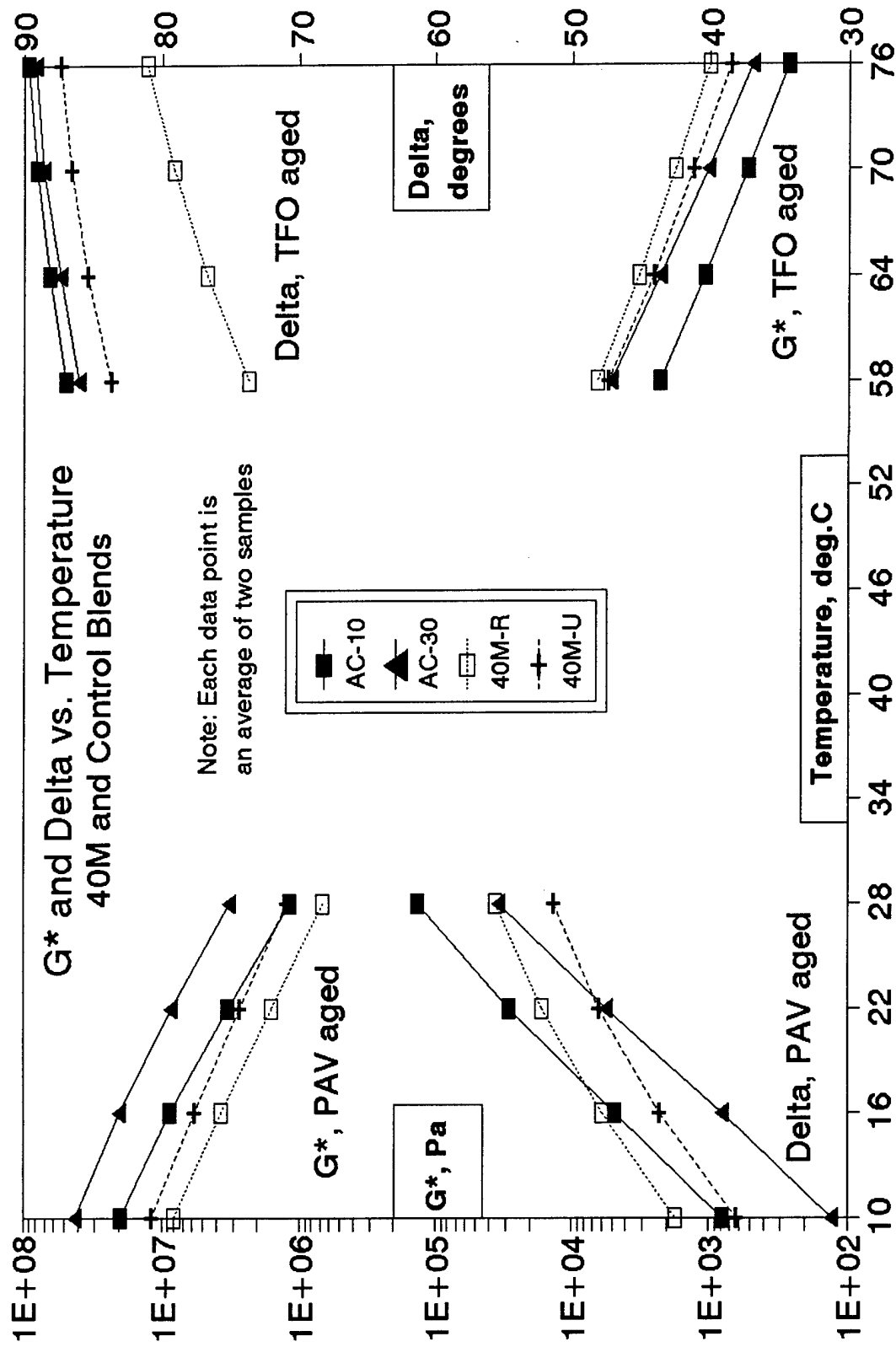


Figure 5.1 G* vs Temperature of 16M and Control Blends

Figure 5.2 δ vs Temperature of 16M and Control Blends

Figure 5.3 G* and δ vs Temperature of 40M and Control Blends

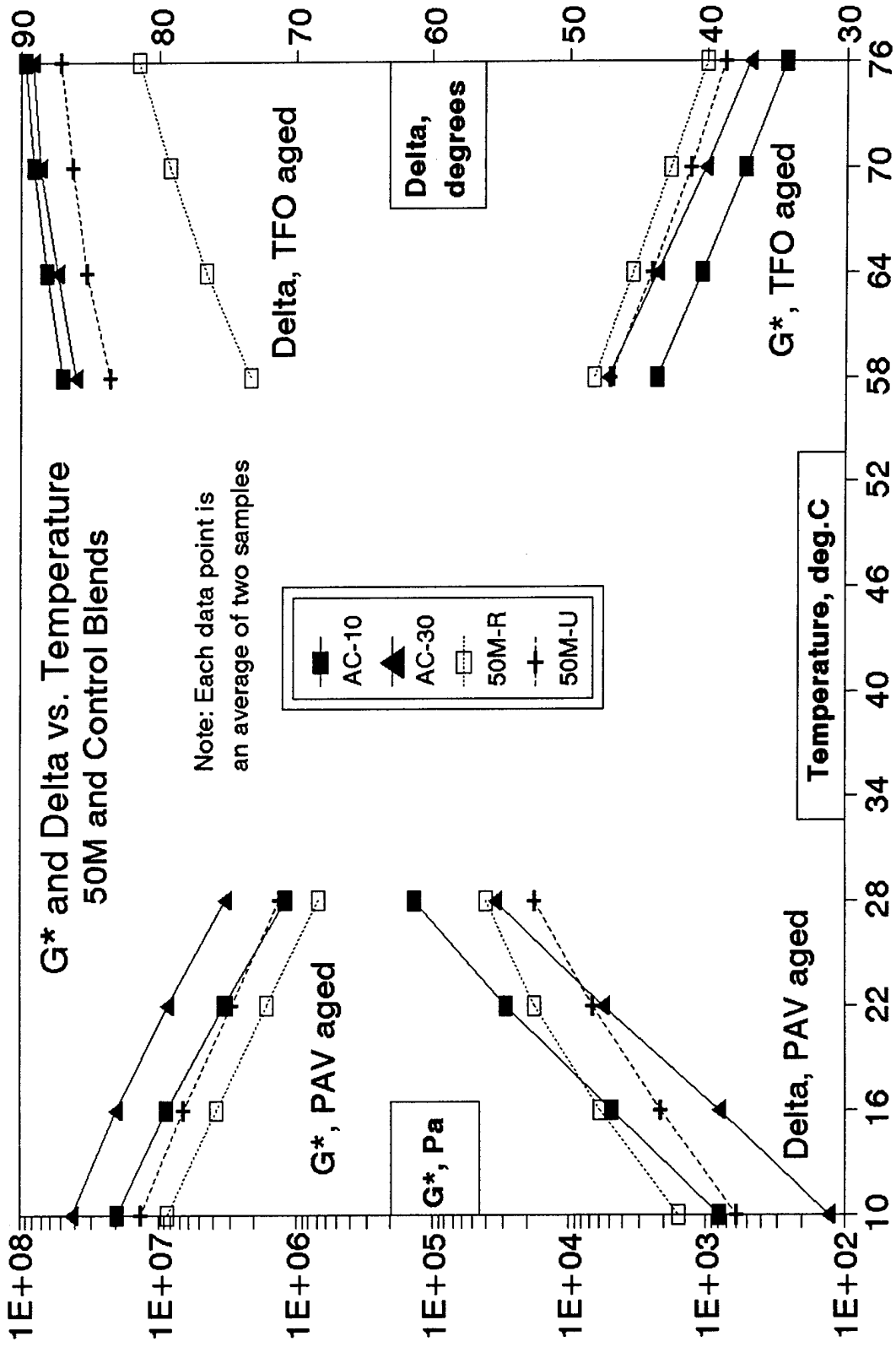
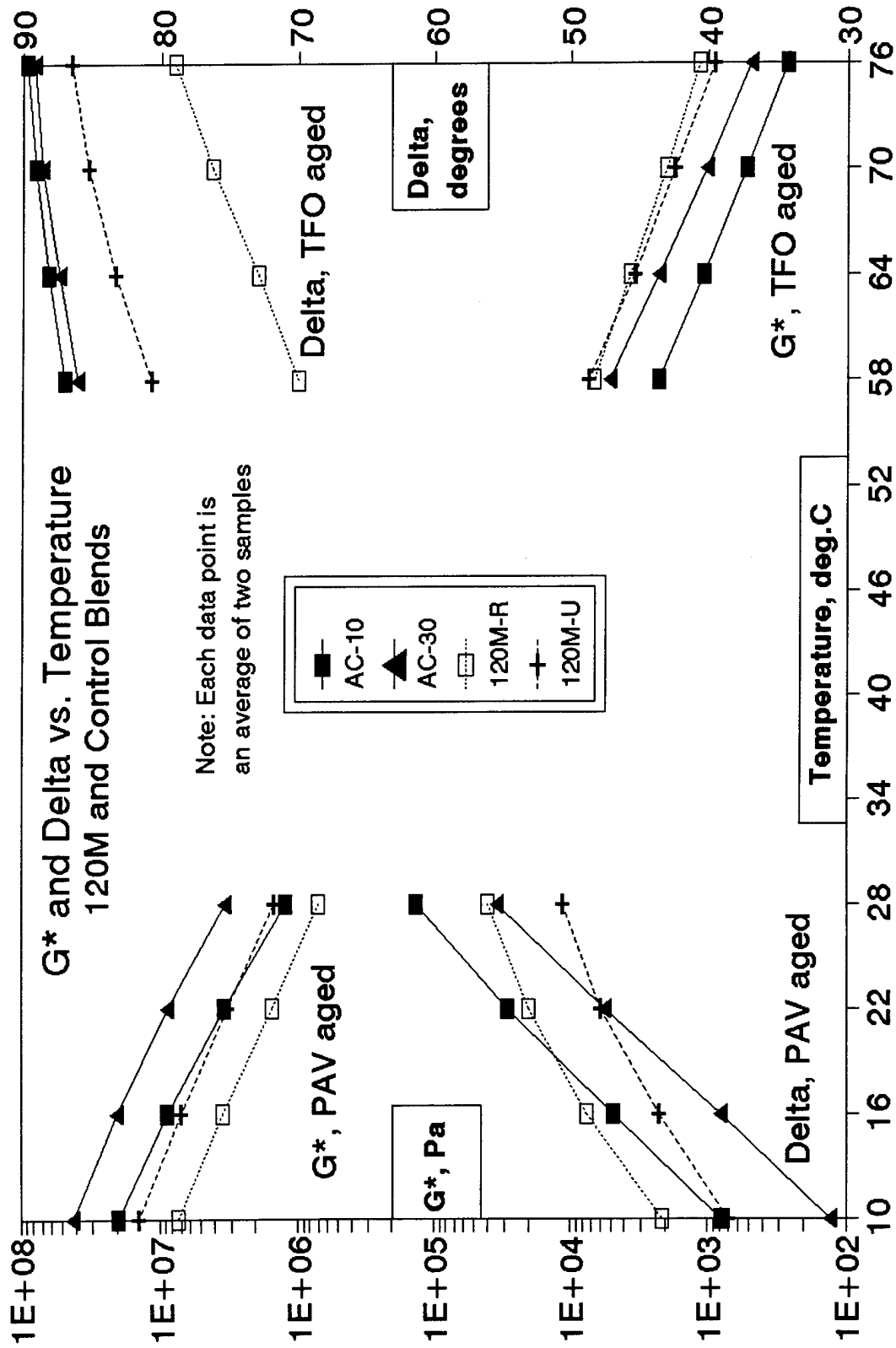


Figure 5.4 G* and δ vs Temperature of 50M and Control Blends

Figure 5.5 G' and δ vs Temperature of 120M and Control Blends

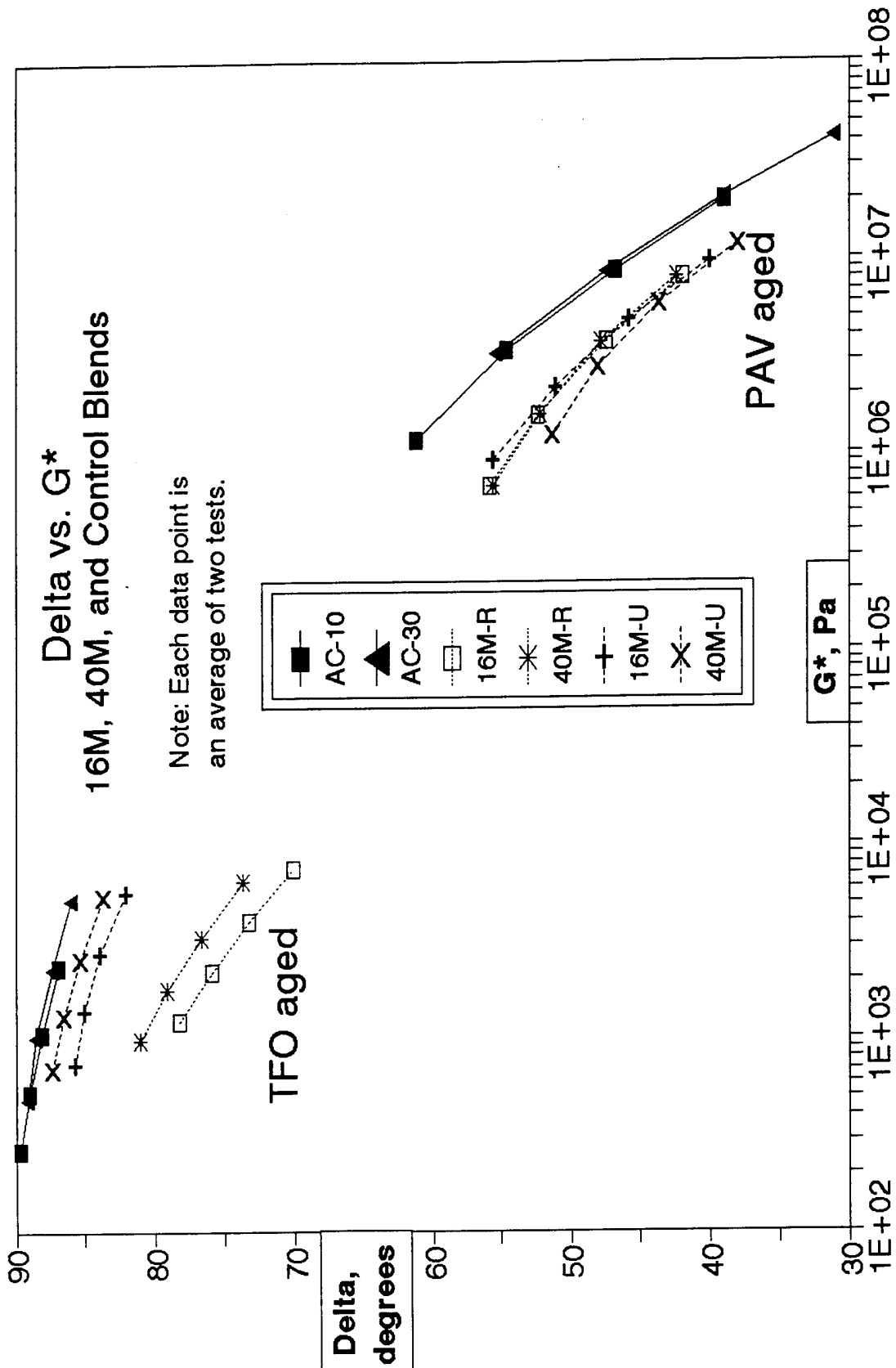
For the G^* vs temperature plots, it is clearly evident at the 58 to 76 °C range (TFO aged binder) that the R blends had the highest stiffness (best), with the U blends having the next highest, and the AC-30 and AC-10 (worst) following respectively. A high stiffness is desired at high temperatures to resist deformation. At the 10 to 28 °C range (PAV aged binder), it is clearly apparent the reverse is true, with the R blends having the lowest stiffness (best), followed by the U blends, and then the AC-10 and AC-30 (worst) respectively. A low stiffness is desired at intermediate temperatures after long-term aging for greater fatigue life. It is clearly demonstrated with these G^* vs temperature plots that not only can high temperature stiffness of an AC be increased by the addition of reacted or unreacted CRM, but the intermediate temperature stiffness can be reduced by doing the same. The latter may be a surprise to some, as generally the addition of particulates increases an AC's stiffness. One simple explanation is that the rubber material itself has a higher stiffness than the AC at the high temperatures, but a lower stiffness than the AC at the lower temperatures.

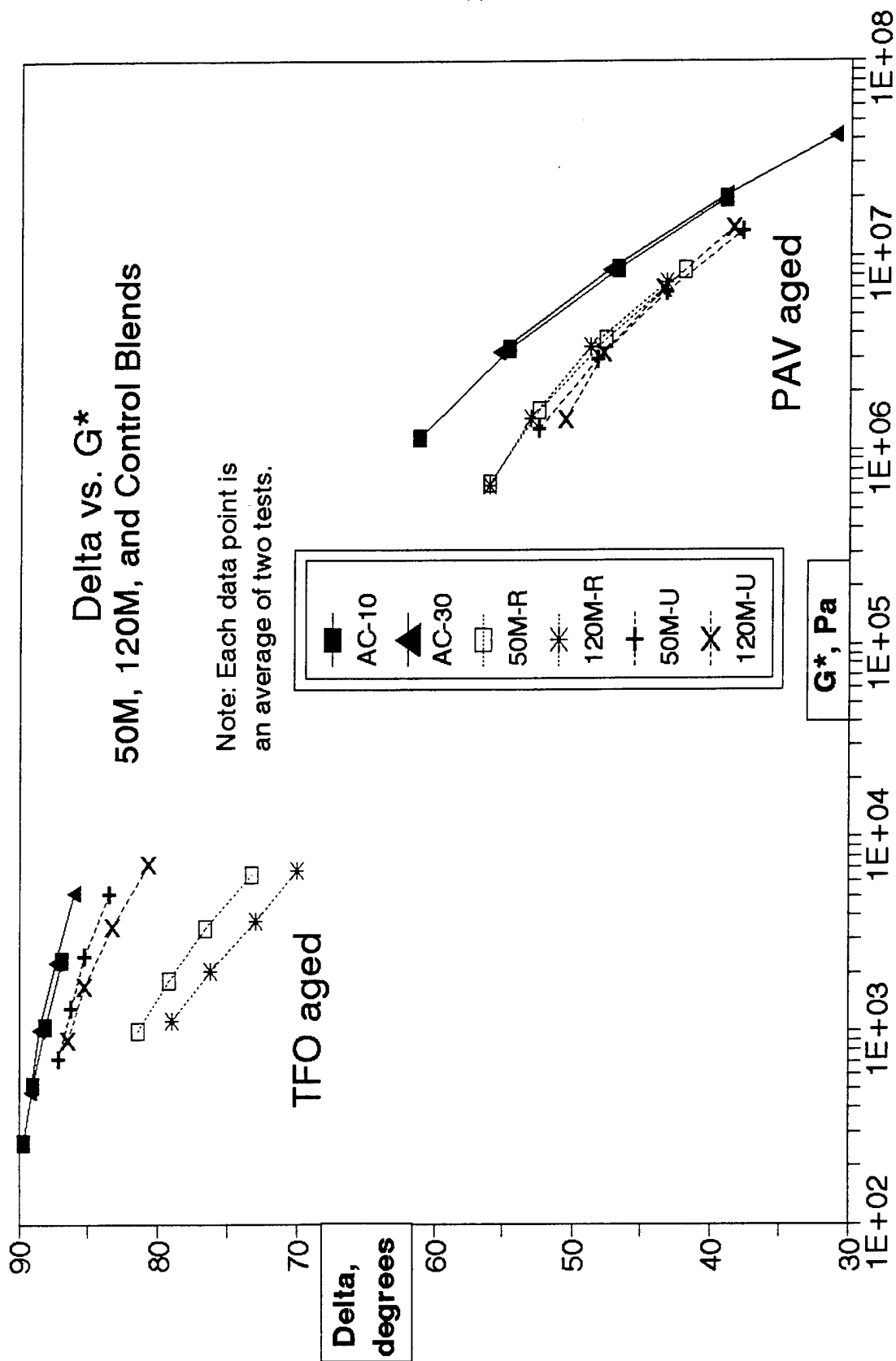
Before examining the δ vs temperature plots, a review of δ may be necessary. Delta (δ) is a measure of the binder's elasticity, or how much the binder will rebound from deformation after unloading. A lower δ angle (measured between 0 and 90°) indicates the binder has less lag between stress and strain than a binder with a higher δ angle, meaning it will recover more from deformation. Thus, a lower δ is desired as it indicates greater elasticity. Elasticity will improve (decrease in δ) when the binder stiffens from either additional aging or a decrease in temperature. This is explained by the fact that a stiffer binder (greater resistance to deformation) will generally recover more of its deformation than a less stiff binder which tends to have more viscous (non-recoverable) deformation. Note that δ always dropped when the same binder was tested at a lower temperature. Also note that the stiffer

AC-30 always showed a lower δ compared to the AC-10 in Figures 5.2 through 5.5, even though both have the same crude source. Thus, differences in δ between the blends tested are from a combination of the CRM effects, as well as the effects of different stiffnesses.

The 58 to 76 °C data (TFO aged) clearly show the R blends having the lowest δ for a given temperature, followed by the U blends and then the two controls. The addition of the reacted or unreacted CRM clearly decreases the δ . It is not clear, however, whether this decrease in δ is due to the CRM making the binder better and more elastic, or just stiffer, which was seen with the G^* vs temperature plots. The same question arises with the 10 to 28 °C data (PAV-aged), as the addition of the CRM decreased G^* , which was desired from a fatigue standpoint, but with this decrease in stiffness also comes an increase in δ . It appears there may be a canceling of effects at these intermediate temperatures, as the addition of CRM improves the relative elasticity (decreasing δ) but also decreases the stiffness which increases δ .

The intention of the next two plots (Figures 5.6 and 5.7) are to compare δ values of the binders for a constant stiffness, removing the effect the different stiffnesses have to δ . Delta vs G^* is plotted in Figure 5.6 for the 16M, 40M and control blends while Figure 5.7 does the same for the 50M, 120M and control blends. The data are the same as used to generate Figures 5.1 through 5.5. The trends are once again almost identical. For the TFO-aged tests, the R blends had the lowest δ for a given G^* (best), with the U blends following and the control blends having the highest (worst). For the PAV-aged tests, the R and U blends had similar δ values for a given G^* , which were significantly lower (better) than the two control blends. It is interesting to note the AC-10 and AC-30 curves are almost identically placed, probably due to having the same crude source.

Figure 5.6 δ vs G^* of 16M, 40M and Control Blends

Figure 5.7 δ vs G^* of 50M, 120M and Control Blends

SUPERPAVE Criteria

For tenderness and rutting, SUPERPAVE binder grading criteria establishes the maximum temperature at which the binder still possesses the minimum required value of $G^*/\sin\delta$, determined from the DSR results. Tenderness criterion establishes the highest temperature at which the unaged binder has a $G^*/\sin\delta$ value no lower than 1.0 kPa. Rutting criterion establishes the highest temperature at which the TFO-aged binder has a $G^*/\sin\delta$ value no lower than 2.2 kPa. It is desired for binders to be able to meet these minimum required $G^*/\sin\delta$ values at high temperatures. This high temperature rating must meet both the tenderness and rutting criteria and is indicated by the first number (high temperature end) of the SUPERPAVE grade (ie. 64°C for a PG64-22 graded binder)(58).

For fatigue, SUPERPAVE criteria establishes the lowest temperature at which the PAV-aged binder has a $G^*(\sin\delta)$ value no higher than 5000 kPa. It is desired for binders to be able to meet this maximum $G^*(\sin\delta)$ value at low temperatures. The way this fatigue temperature rating is used in determining the second number of the SUPERPAVE grade (low temperature end) is somewhat complex and its explanation is not critical to this report (58).

Figure 5.8 is a plot of the tenderness parameter ($G^*/\sin\delta$ for unaged binder) vs temperature, with the 16M, 40M and control blends on the top half of the figure and the 50M, 120M and control blends on the bottom half of the figure. This format was chosen for clarity because the four R blends tended to fall on top of one another, as well as the four U blends. Each data point at the four temperatures is an average of two test samples whose overall average CV within these two repetitions was only 2.57%. Thus, any visual difference on the log scale is generally significant. The minimum tenderness criteria of 1 kPa is shown as a horizontal dashed line to indicate the maximum temperature at which each blend meets this criterion.

Figure 5.9 uses the same format as Figure 5.8, but plots the rutting parameter ($G^*/\sin\delta$ for TFO-aged binder) vs temperature. The minimum criterion of 2.2 kPa is shown to indicate the maximum temperature at which each blend meets this criterion. Again, the overall average CV was very small at 2.66%.

Figures 5.10 and 5.11 plot the fatigue parameter [$G^*(\sin\delta)$ for PAV-aged binder] vs temperature. Figure 5.10 plots the 16M blends (including 16M-PAV) and control blends on top and the 40M and control blends on the bottom. Figure 5.11 is identical, but with the 50M and 120M blends. The maximum fatigue criterion of 5000 kPa is shown to indicate the minimum temperature at which each blend meets this criterion. The overall average CV of $G^*(\sin\delta)$ was 5.20%.

Figures 5.8 through 5.11 clearly show that for all CRM sizes, the R blends performed the best for tenderness and rutting (having the highest parameter values), as well for fatigue (having the lowest parameter values). The U blends also outperformed both controls, but not the R blends, with all the CRM sizes for tenderness, rutting and fatigue. Further performance comparisons are made after Figure 5.11.

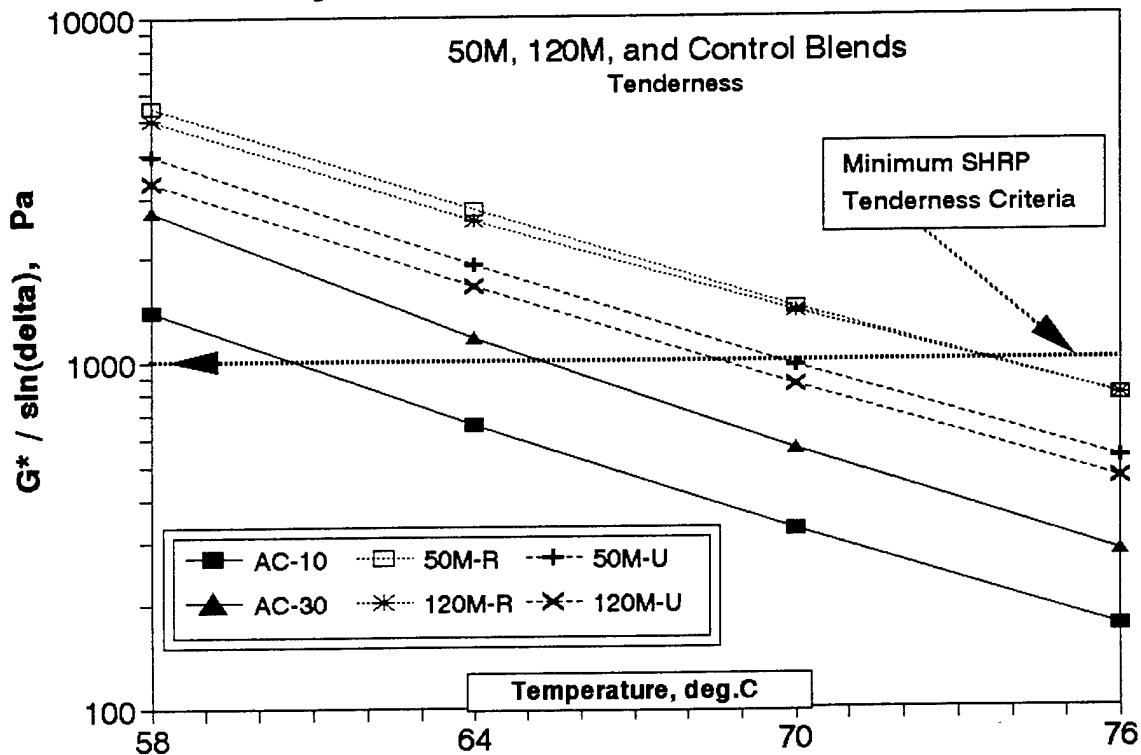
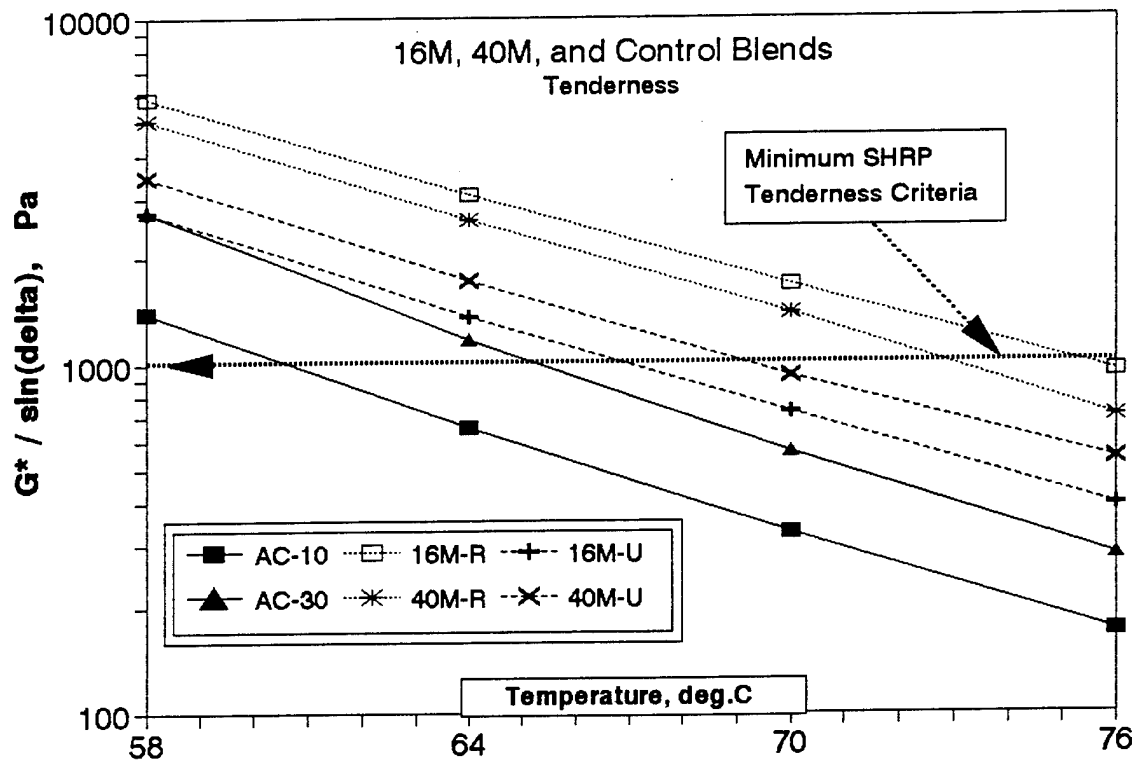
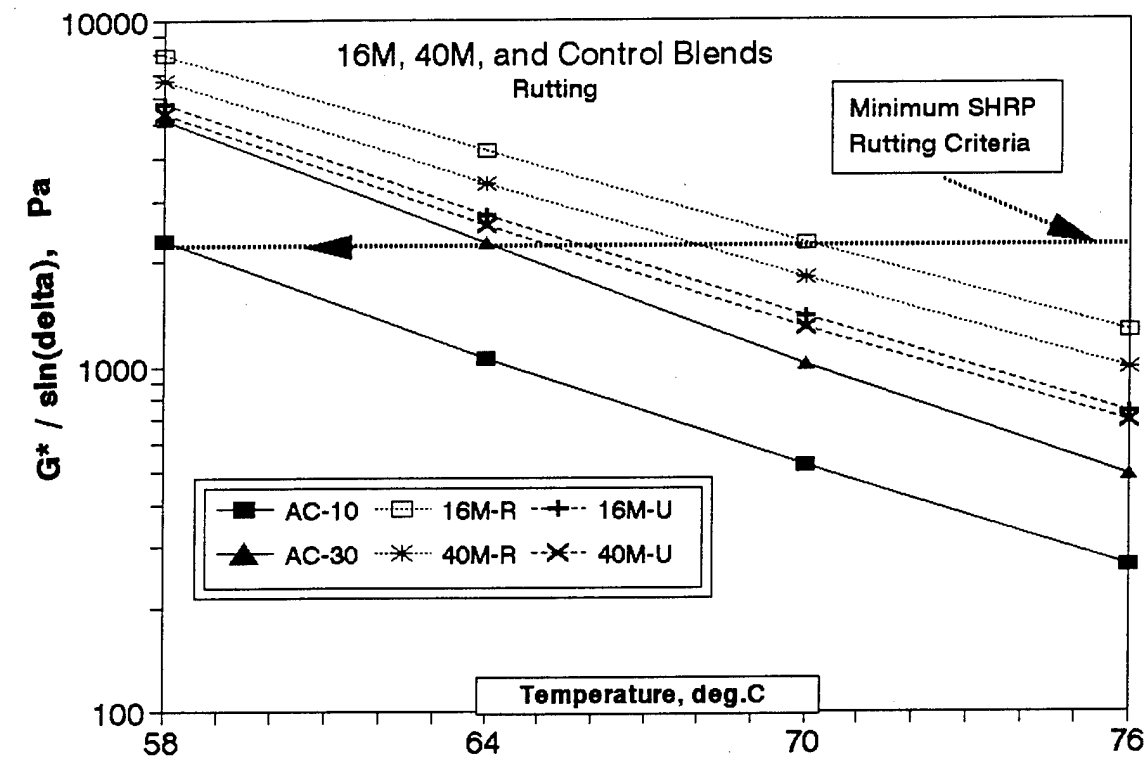


Figure 5.8 Tenderness Parameter vs Temperature of All 10 Blends



note: Each data point is an average from two tests.

The average CV within these two repetitions for $G^*/\sin(\delta)$ was 2.66%.

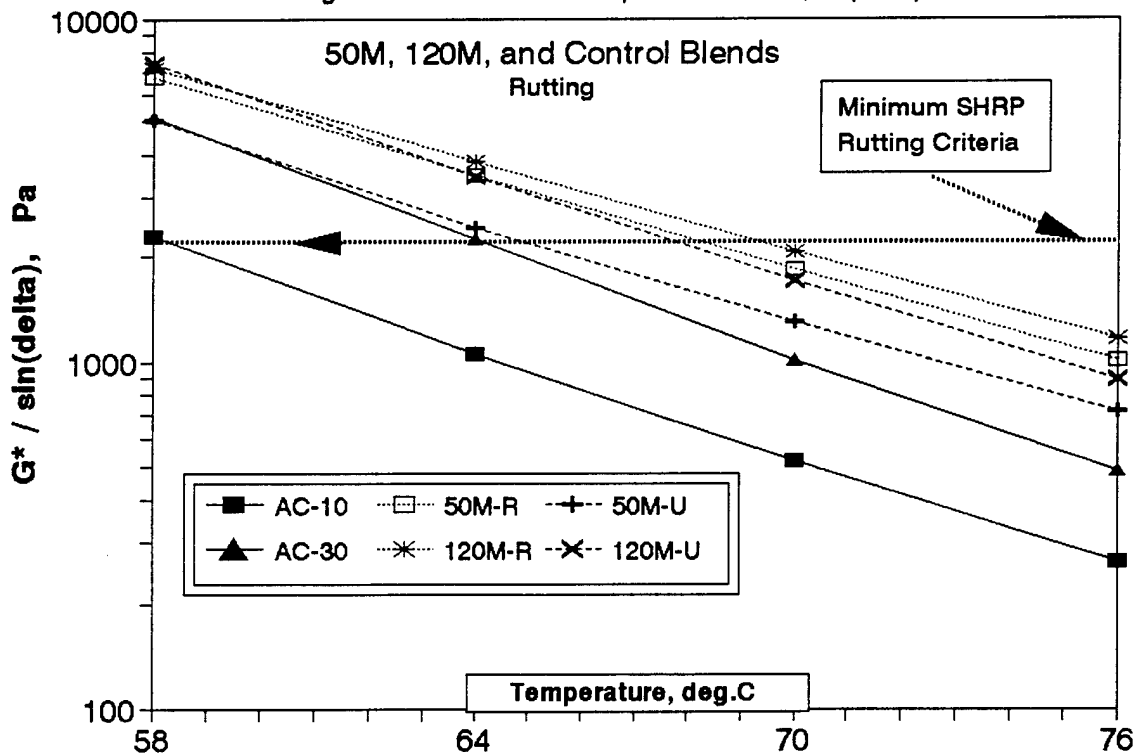


Figure 5.9 Rutting Parameter vs Temperature of All 10 Blends

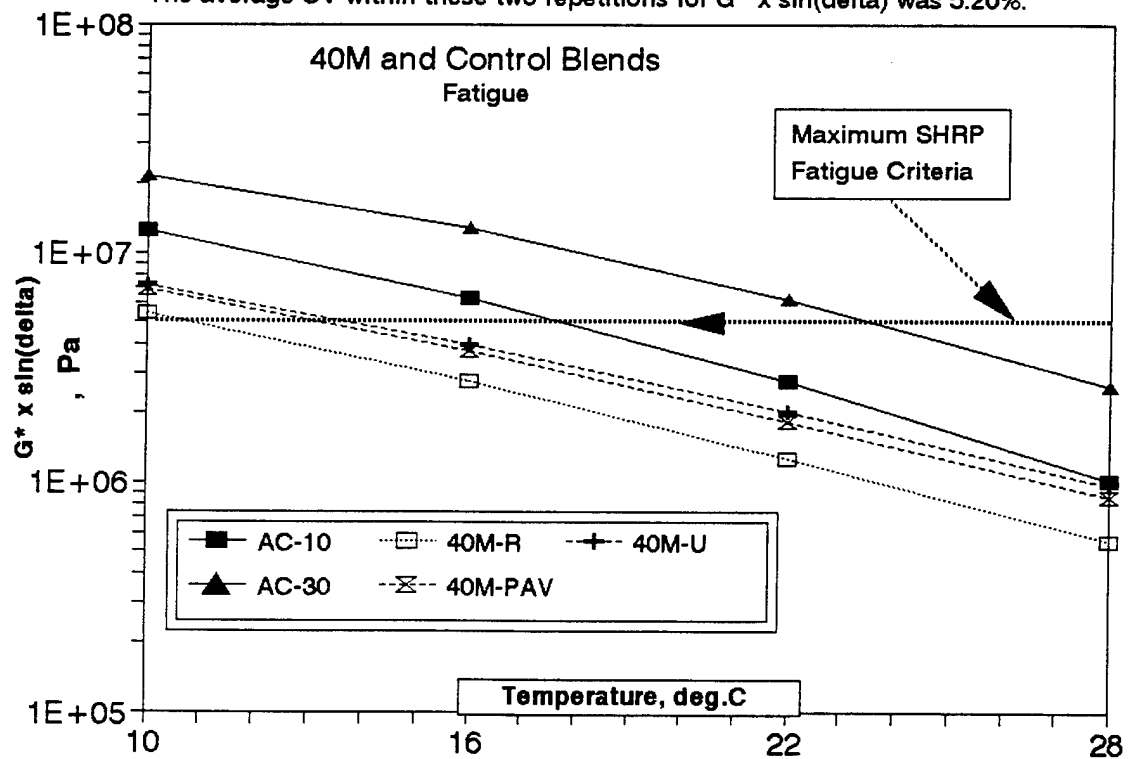
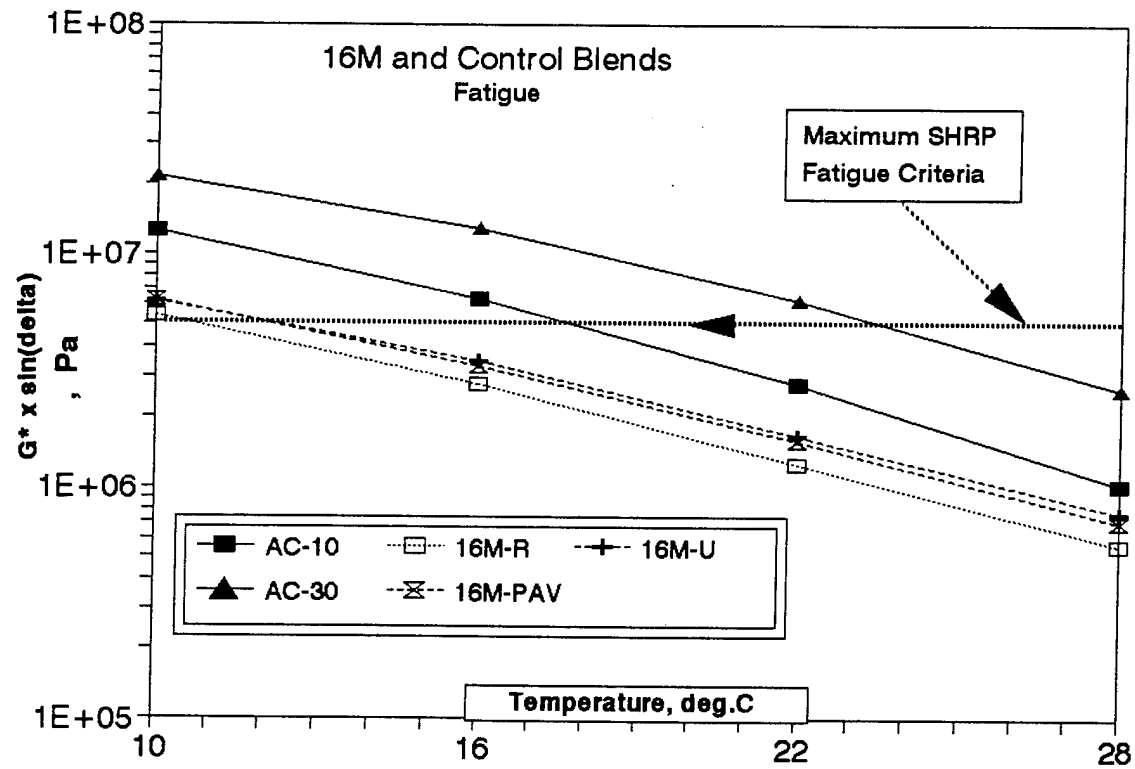
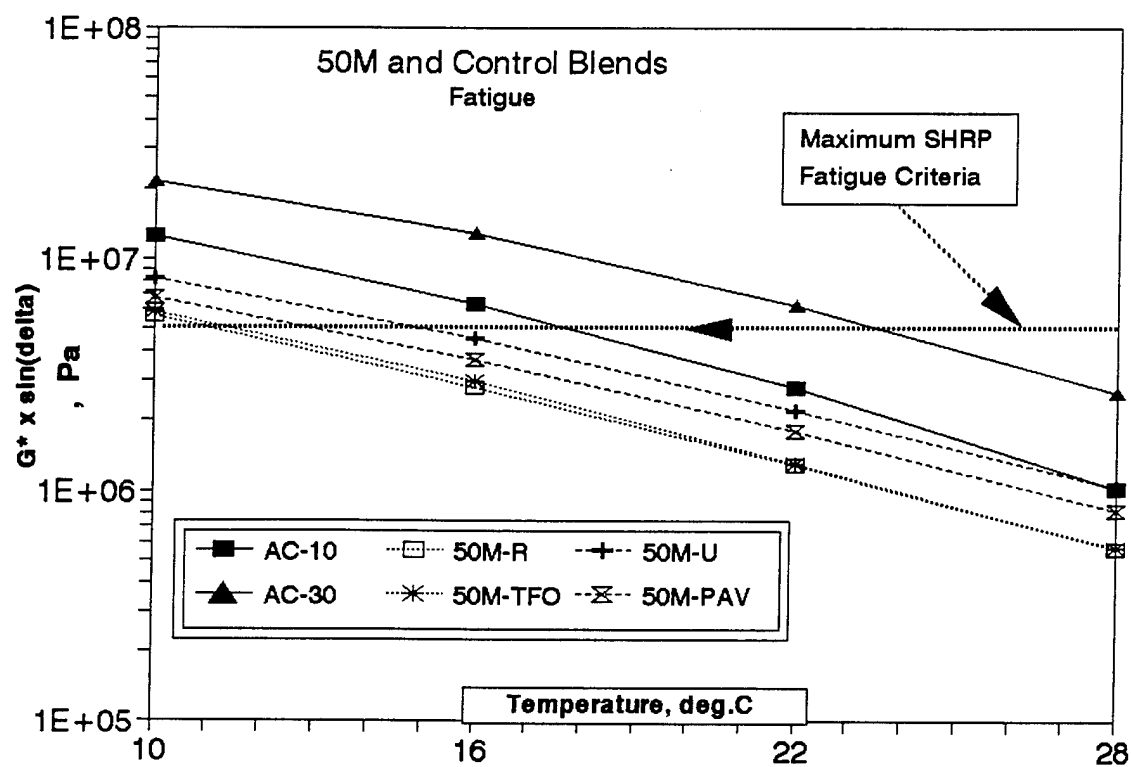


Figure 5.10 Fatigue Parameter vs Temperature of 16M, 40M and Control Blends



note: Each data point is an average from two tests.

The average CV within these two repetitions for $G^* \times \sin(\delta)$ was 5.20%.

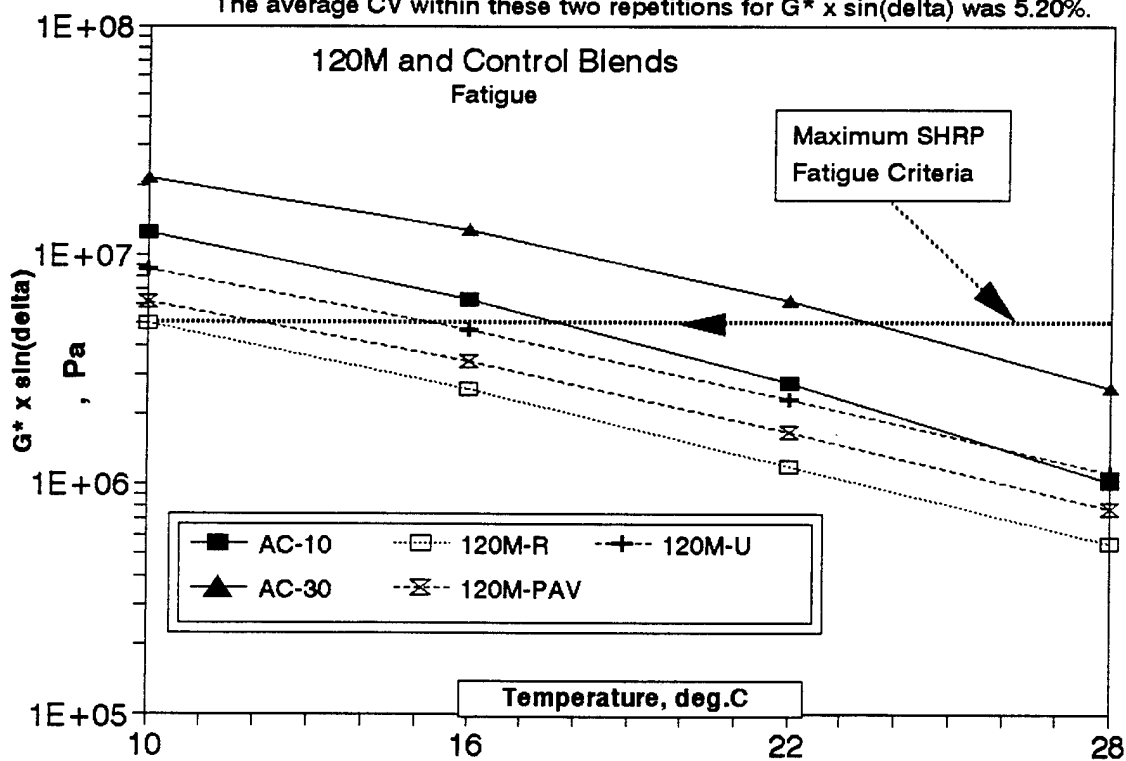


Figure 5.11 Fatigue Parameter vs Temperature of 50M, 120M and Control Blends

Table 5.1 summarizes Figures 5.8 through 5.11 by listing, for each blend, the maximum test temperatures at which the tenderness and rutting criteria were met, and the minimum test temperature the fatigue criterion was met. For those familiar with the SUPERPAVE grading system, perspective is put on the differences in the blends.

Table 5.1 Test Temperature Extremes at Which SUPERPAVE Criteria with DSR Were Met

| Blend | Maximum test temp. ($^{\circ}\text{C}$) at which Tenderness criterion is met $G^*/\sin\delta \geq 1.0 \text{ kPa}$ | Maximum test temp. ($^{\circ}\text{C}$) at which Rutting criterion is met $G^*/\sin\delta \geq 2.2 \text{ kPa}$ | Minimum test temp. ($^{\circ}\text{C}$) at which Fatigue criterion is met $G^*(\sin\delta) \leq 5.0 \text{ MPa}$ |
|----------|---|--|---|
| AC-10 | 60 | 58 | 18 |
| AC-30 | 65 | 64 | 24 |
| 16M-R | 75 | 70 | 10 |
| 40M-R | 73 | 68 | 10 |
| 50M-R | 74 | 68 | 11 |
| 120M-R | 74 | 69 | 10 |
| 16M-U | 67 | 66 | 12 |
| 40M-U | 69 | 65 | 13 |
| 50M-U | 70 | 65 | 15 |
| 120M-U | 69 | 68 | 15 |
| 16M-PAV | - | - | 12 |
| 40M-PAV | - | - | 13 |
| 50M-PAV | - | - | 13 |
| 120M-PAV | - | - | 12 |
| 50M-TFO | - | 68 | 11 |

Figures 5.8 through 5.11 and Table 5.1 clearly show that by adding reacted or unreacted CRM to an AC-10, the tenderness and rutting performance exceeds that of an AC-30. For fatigue, the addition of reacted or unreacted CRM will improve performance of the base AC as well by making the binder less stiff (lower G^*) and more elastic (lower δ). This is surprising because generally, adding fine particles (like dust) will stiffen a binder. The CRM, however, caused a decrease in stiffness at the lower temperatures. The R blends always outperformed the U blends, which always outperformed both control blends. The control blends performed as expected, with the AC-30 being better than the AC-10 for tenderness and rutting, and the AC-10 being better than the AC-30 for fatigue.

Note the rutting criterion always provided a lower maximum acceptable temperature than the tenderness criterion. This is inconsistent with most other binders being graded using SUPERPAVE, where tenderness often controls (64). The inconsistency can be explained because the RTFO is used with SUPERPAVE procedures, which has been shown to provide more aging and stiffening of the binder than the TFO used in this project (65).

As opposed to complete testing of the ten primary blends, only partial testing was performed on the five supplemental blends. In the four supplemental PAV blends, the CRM was not added to the TFO-aged AC-10 until just prior to the PAV. In the one TFO supplemental blend, the CRM was added to the unaged AC-10 just prior to the TFO. It is apparent by looking at the PAV blends in Figures 5.10 and 5.11 that a partial reaction occurred during the PAV aging process. This is because in all cases, the PAV blends fell between the U and the R blends. For the larger CRM sizes, the PAV blend performance is very close to the U blend performance, while for the finer CRM sizes, the PAV blend performance gets closer to the R

blend performance. This makes sense as more reaction would likely take place in the PAV for the finer CRM.

The 50M-TFO blend was prepared very early in the test program to determine how much reaction occurs during TFO-aging. It is apparent from Figure 5.11 that nearly a full reaction occurs, as the 50M-TFO data are extremely close to the 50M-R data. The results seem to indicate that more reaction occurs in the TFO aging process (163°C for 5 hours) than the PAV aging process (100°C @ 300psi for 20 hours).

CRM Gradation Effects

It has been apparent thus far that the CRM gradation (particle size) has had a relatively small effect on G^* , δ and the SUPERPAVE high temperature performance parameters. Closer examination is provided with Figures 5.12 and 5.13, but a note of caution is needed. Since comparing the reacted and unreacted blends was the primary concern and determining the CRM gradation effects was secondary, all aging of the blends was performed with the reacted and unreacted blends of the same CRM size paired together through the same aging cycle. Each CRM size had a separate aging cycle. This means any differences present among the TFO or PAV aging cycles would likely show up as differences in CRM gradation effects.

Figure 5.12 plots the rutting parameter ($G^*/\sin\delta$ for TFO-aged blends) on log scale in relation to the CRM nominal maximum size, at each of the 4 test temperatures. One should be aware that the CRM sizes are not displayed to scale on the horizontal axis. The AC-10 and AC-30 data are shown as well to put in perspective the subtle trends to be discussed. The 40M and 50M values are lower than the 16M and 120M values. It is also apparent that the 120M-U blend is closer to the 120M-R blend than is the case with the 16M, 40M or 50M blends. This may

be due to some instantaneous reaction taking place during the blending of the 120M-U blend, because the CRM is so fine and the TFO-aged base AC still has sufficient aromatic oils present for reaction.

Figure 5.13 is similar to Figure 5.12 but plots the fatigue parameter $[G^*(\sin \delta)$ for PAV-aged blends]. The predominant trend here is as the CRM gets finer, the U blends get closer to the AC-10 and further from the R blends. This suggests there is little or no reaction taking place during the blending of the unreacted CRM with the PAV-aged AC-10. If some reaction was occurring, the U blend parameter would likely approach the R blend parameter as the CRM becomes finer. This trend can be explained because there likely is little or no aromatic oils available in the AC-10 after PAV aging for the CRM to react with. A related trend is that the larger unreacted CRM particles appear to have a slightly better effect in terms of fatigue than the finer CRM.

It appears the effect of changing the CRM gradation on the SUPERPAVE parameters is small in relation to the overall effect of adding reacted or unreacted CRM to an asphalt. The BBR results which follow also show CRM gradation to have relatively little effect on the S or m parameters. These findings are consistent with another NCAT CRM binder study (29) which found CRM gradation to have a relatively small effect on the SUPERPAVE parameters when compared to the effect of the addition of CRM.

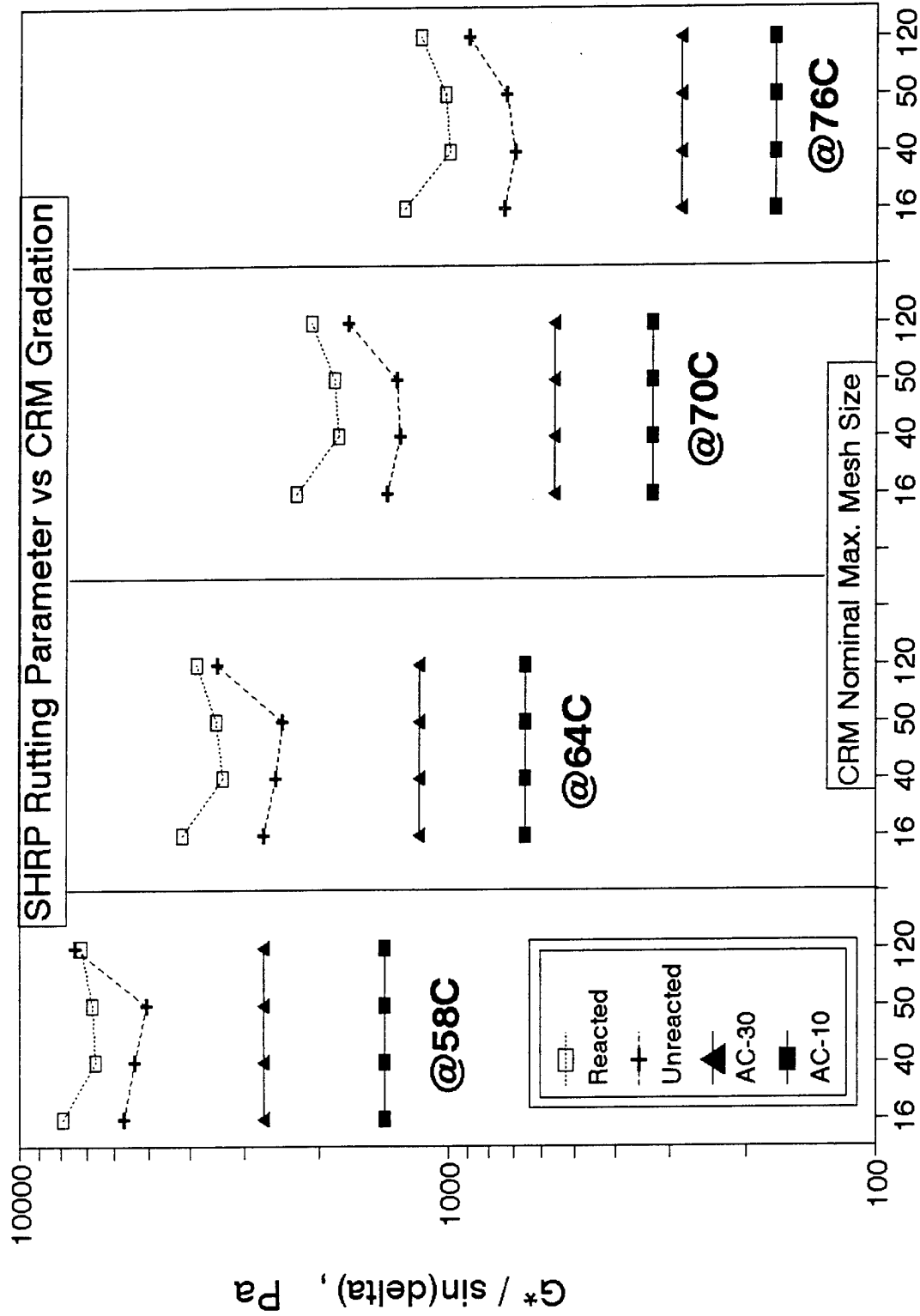


Figure 5.12 CRM Particle Size Comparison with the Rutting Parameter

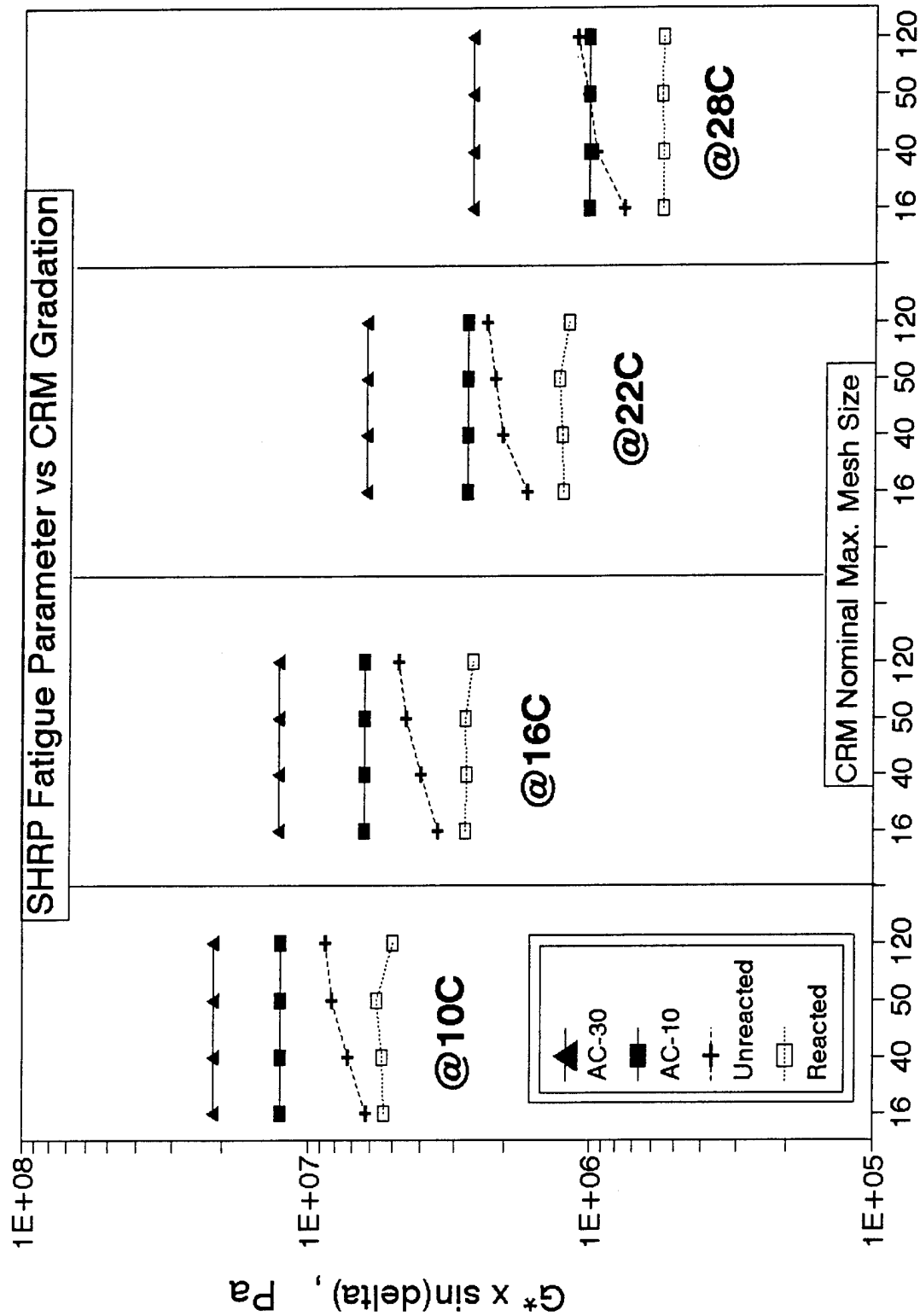


Figure 5.13 CRM Particle Size Comparison with the Fatigue Parameter

Aging Ratios

Aging ratios are calculated by taking a stiffness parameter of a specimen after a controlled amount of aging and dividing it by the same stiffness parameter measured on the same specimen before aging. These ratios are then compared to the ratios of other treatments obtained the same way to determine relative aging characteristics of the treatments. A low binder aging ratio is desired so the binder will age slowly in the field and not become prematurely brittle.

TFO aging ratios were calculated for each of the four temperatures by taking the average G^* after TFO and dividing by the average G^* before TFO. These ratios are shown in Table 5.2. Only the control and R blends are tabulated because the U blends had only the base AC aged in the TFO and not the CRM.

The average and standard deviation of the four ratios for each blend are also shown in Table 5.2. It is apparent the R blends generally have lower aging ratios (better) than the control blends, with the mean differences exceeding the standard deviations by sizable amounts. This infers the wet process CRM binders age slower than unmodified binders, but this analysis is somewhat limited because the Phase I test plan was not designed with aging comparisons as the primary objective. If it was, aging in the PAV with a harsher environment would have been used as well as a better aging randomization plan. The aging plan was designed for direct comparisons of reacted and unreacted blends. The AC-30 having a higher aging ratio than the AC-10 cannot be explained, other than the aging cycles were different and there was no aging cycle replication.

Table 5.2 TFO Aging Ratios on Control and Reacted Blends

| Blend | Ratio of Average G^* after TFO (2 reps) to Average G^* before TFO (2 reps). | | | | Average Aging Ratio (from 4 temps.) | Standard Deviation (from 4 temps.) |
|--------|--|-------|-------|-------|---|---|
| | 58 °C | 64 °C | 70 °C | 76 °C | | |
| AC-10 | 1.63 | 1.62 | 1.59 | 1.55 | 1.60 | .04 |
| AC-30 | 1.90 | 1.95 | 1.80 | 1.72 | 1.84 | .10 |
| 16M-R | 1.35 | 1.34 | 1.32 | 1.31 | 1.33 | .02 |
| 40M-R | 1.29 | 1.28 | 1.29 | 1.40 | 1.32 | .05 |
| 50M-R | 1.23 | 1.24 | 1.26 | 1.26 | 1.25 | .02 |
| 120M-R | 1.38 | 1.45 | 1.45 | 1.44 | 1.43 | .03 |

BBR and DTT TESTING

The results of all the individual BBR and DTT tests under this test plan are tabulated in Appendix C. Table C.1 lists the S and m values of all three BBR sample repetitions, as well as an average, standard deviation and CV, for all blends tested. This includes the 10 primary blends and the supplemental 50M-TFO blend. Table C.2 lists the ϵ_f and peak stress of all 12 DTT sample repetitions, as well as averages and the standard deviation of ϵ_f , for the same 11 blends.

Results at -18 °C

Table 5.3 summarizes the BBR and DTT results obtained at -18 °C. The average and standard deviation (s) of S , m , and ϵ_f for the 11 blends are listed. This includes the 10 primary blends and one supplemental blend, the 50M-TFO.

Table 5.3 BBR and DTT Results at -18 °C (averages and standard deviations)

| Blend | BBR @ -18 °C (3 reps) | | | | DTT @ -18 °C (12 reps) | |
|---------|-----------------------|------|------|------|------------------------|-------|
| | S, MPa | | m | | ϵ_f , % | |
| | Avg. | s | Avg. | s | Avg. | s |
| AC-10 | 282.3 | 6.4 | .307 | .006 | .2613 | .1240 |
| AC-30 | 427.0 | 9.2 | .247 | .006 | .1057 | .0336 |
| 16M-R | 128.0 | 4.0 | .323 | .006 | .4542 | .0895 |
| 40M-R | 133.3 | 3.1 | .327 | .012 | .4770 | .1534 |
| 50M-R | 112.3 | 2.9 | .333 | .006 | .4776 | .0965 |
| 120M-R | 124.3 | 1.2 | .340 | .000 | 1.8507 | .2287 |
| 16M-U | 179.7 | 8.1 | .300 | .000 | .0910 | .0420 |
| 40M-U | 187.7 | 16.6 | .293 | .006 | .1731 | .0335 |
| 50M-U | 198.0 | 12.5 | .297 | .006 | .1880 | .0424 |
| 120M-U | 196.7 | 2.3 | .300 | .000 | .2760 | .1162 |
| 50M-TFO | 123.3 | 4.9 | .310 | .000 | .4506 | .2380 |

For the S parameter, the R blends clearly have the smallest values (best), the U blends next, then the AC-10 and finally the AC-30 had the highest (worst). By noting the small standard deviations, it is clear these differences between groups are statistically significant. Thus, the presence of reacted or unreacted CRM to the AC-10 decreased the S value. The 50M-TFO blend again had values close to the 50M-R blend, indicating the CRM fully reacted in the TFO.

For the m parameter, the differences are not quite as large. The R blends had the highest values (best), the AC-10 and U blends next, and finally the AC-30 had the lowest (worst). Thus, the presence of reacted CRM to the AC-10 increased the m value, but adding unreacted CRM did not. However, the R and U blends clearly had better m values than the AC-30.

For the ϵ_f parameter, the variance was high relative to that for the S and m values. The R blends had the highest values (best again), the 120M-U and AC-10 were next, then the 50M-U and 40M-U, and finally the AC-30 and 16M-U had the smallest values (worst). Notice that as the CRM became finer for the R or U blends, ϵ_f increased. An explanation for this may be that the finer CRM blends act more as a homogeneous composite. This could improve failure behavior by not having the larger discontinuities in the composite that could lead to irregular stress patterns. The R blends may also be acting more homogeneously than the U blends since the reacted CRM particles have softened, while the unreacted CRM have not. Another theory as to why the U blends had relatively poor performance is that tiny air bubbles may have been generated when the CRM was added and then entrapped when the sample was poured. This would have caused ϵ_f to decrease.

SUPERPAVE Criteria

To put the differences of Table 5.3 in perspective, a SUPERPAVE parameter vs temperature plot, as was done for the DSR parameters, was desired. This could not be accomplished with the existing data because tests were only conducted at -18°C . Thus, values at -12 and -24°C were obtained by: 1) using data from a related NCAT study (60), which used the same equipment, procedures, and material and 2) the author running additional tests. All this -12 and -24°C data will be referred to as "auxiliary" BBR data, and is summarized in Table 5.4 for each of the 10 primary blends. Listed are averages of two sample repetitions. For the blends which were not used in the related NCAT study and required additional testing, only the temperature needed to cross the SUPERPAVE criteria was tested.

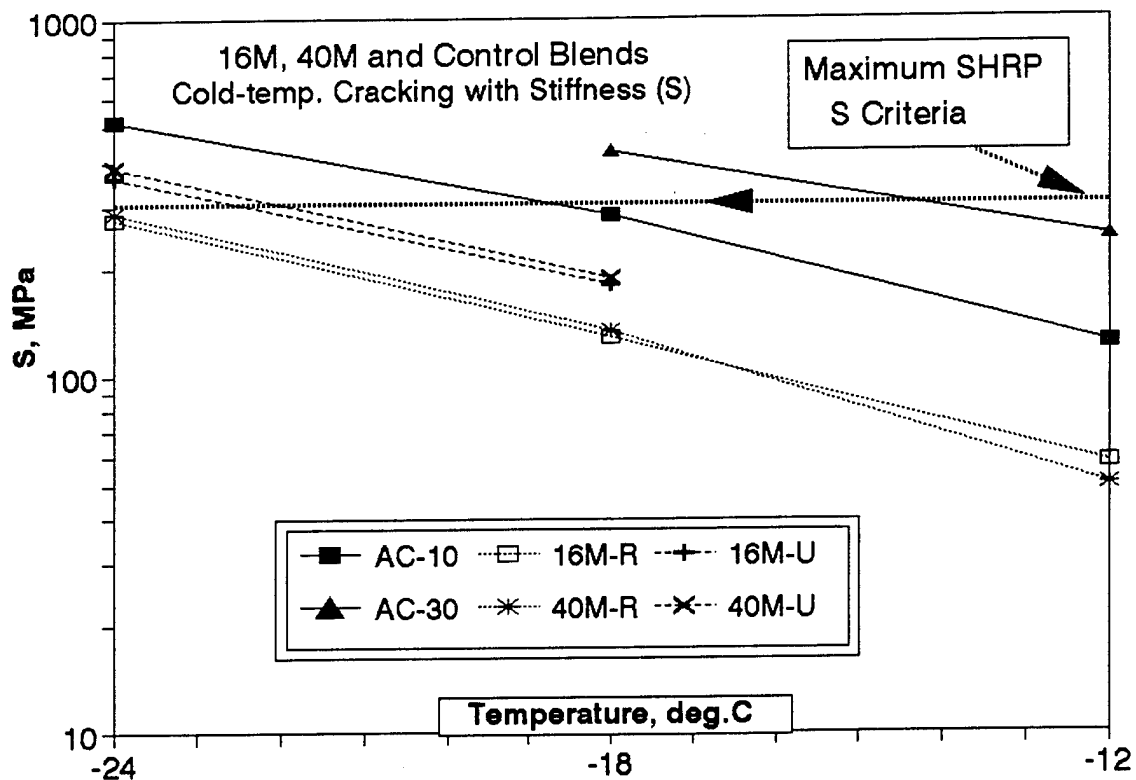
This same type of analysis was not done for the ϵ_f parameter for two reasons. First, the DTT is not routinely used with the SUPERPAVE grading process and is

only needed in special cases (58). Secondly, and more important, the relationship between ϵ_f (or $\log \epsilon_f$) and temperature is not linear. Some tests were run on the same blend at different temperatures to determine if a relationship was evident. The results indicated ϵ_f will slowly increase as temperature increases when in the brittle range ($\epsilon_f < .5\%$), until a certain temperature is reached where ϵ_f will increase rapidly, well above the minimum criteria of 1%. A temperature interval much smaller than 6°C would be needed to accurately determine the minimum temperature at which $\epsilon_f = 1\%$.

Table 5.4 Auxiliary BBR Results at -12°C and -24°C (averages)

| Blend | Note | @ -12°C (2 reps) | | @ -24°C (2 reps) | |
|---|------|------------------|----------|------------------|----------|
| | | S, MPa (avg.) | m (avg.) | S, MPa (avg.) | m (avg.) |
| AC-10 | * | 123 | .36 | 519 | .22 |
| AC-30 | # | 245 | .31 | - | - |
| 16M-R | * | 57 | .38 | 275 | .26 |
| 40M-R | * | 50 | - | 287 | .28 |
| 50M-R | * | 48 | .39 | 262 | .28 |
| 120M-R | * | 47 | .41 | 247 | .28 |
| 16M-U | # | - | - | 361 | .24 |
| 40M-U | # | - | - | 386 | .20 |
| 50M-U | # | - | - | 347 | .22 |
| 120M-U | # | - | - | 372 | .23 |
| <p>Notes: * - the data were obtained from a related NCAT study using the same equipment, procedures, CRM size and concentration, and AC-10 (60).</p> <p># - the data were from tests performed by the author under this research effort.</p> | | | | | |

Figure 5.14 is a plot of $\log_{10} S$ vs temperature while Figure 5.15 is a plot of m versus temperature. Both relationships appear fairly linear, so a straight line connects the values for each temperature. The 16M, 40M and control blends are plotted at the top of each figure while the 50M, 120M and control blends are plotted on the bottom of each. The maximum SUPERPAVE S criterion and the minimum SUPERPAVE m criterion are annotated to determine the minimum temperatures at which each criterion is met. These minimum temperatures for each blend are summarized in Table 5.5. The m value was always more critical than the S values by providing a higher minimum temperature, which is typical with the SUPERPAVE classification system.



note: The -18C data points are an average from 3 test samples.
The average standard deviation within these 3 repetitions for S was 6.5 MPa.

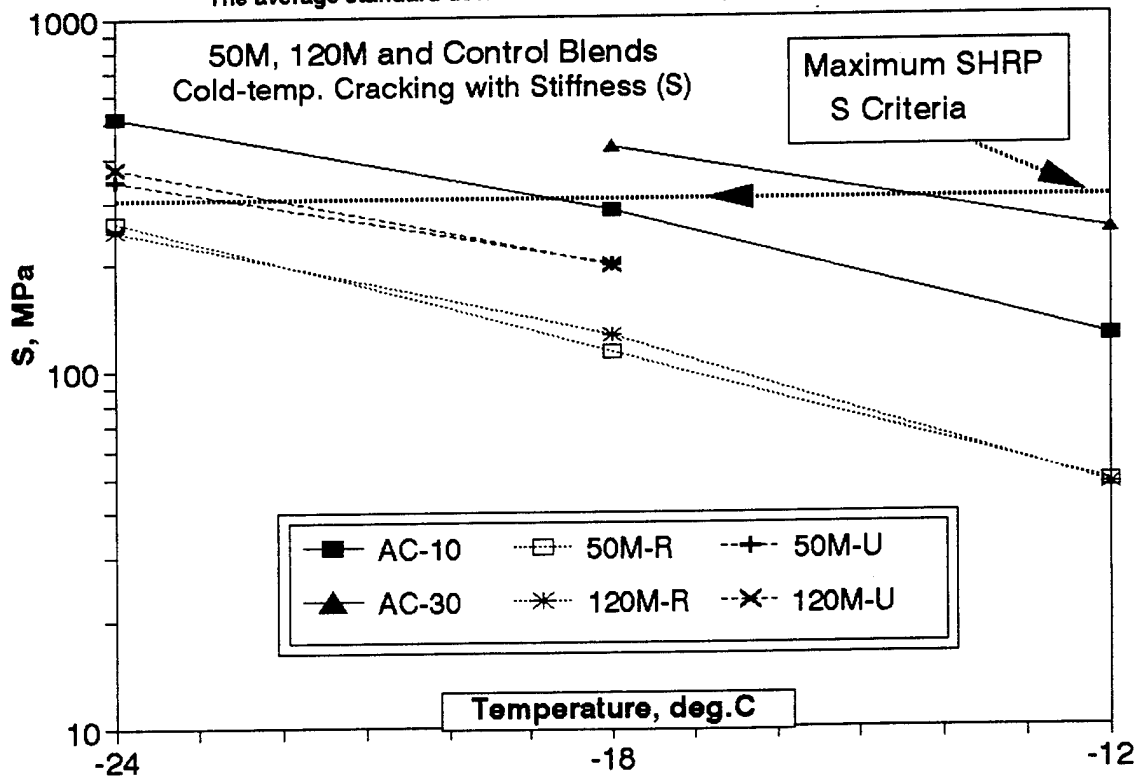
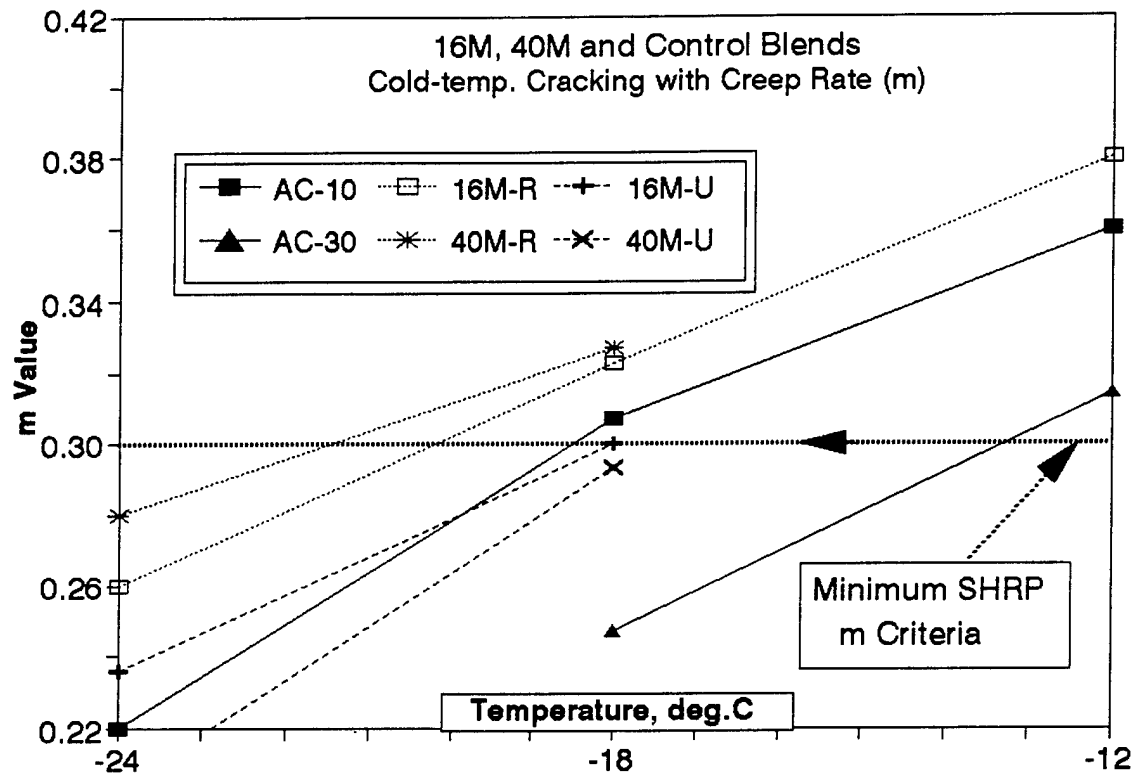


Figure 5.14 BBR Stiffness (S) vs Temperature of All Blends



note: The -18C data points are an average from 3 test samples.
The average standard deviation within these 3 repetitions for m was .004.

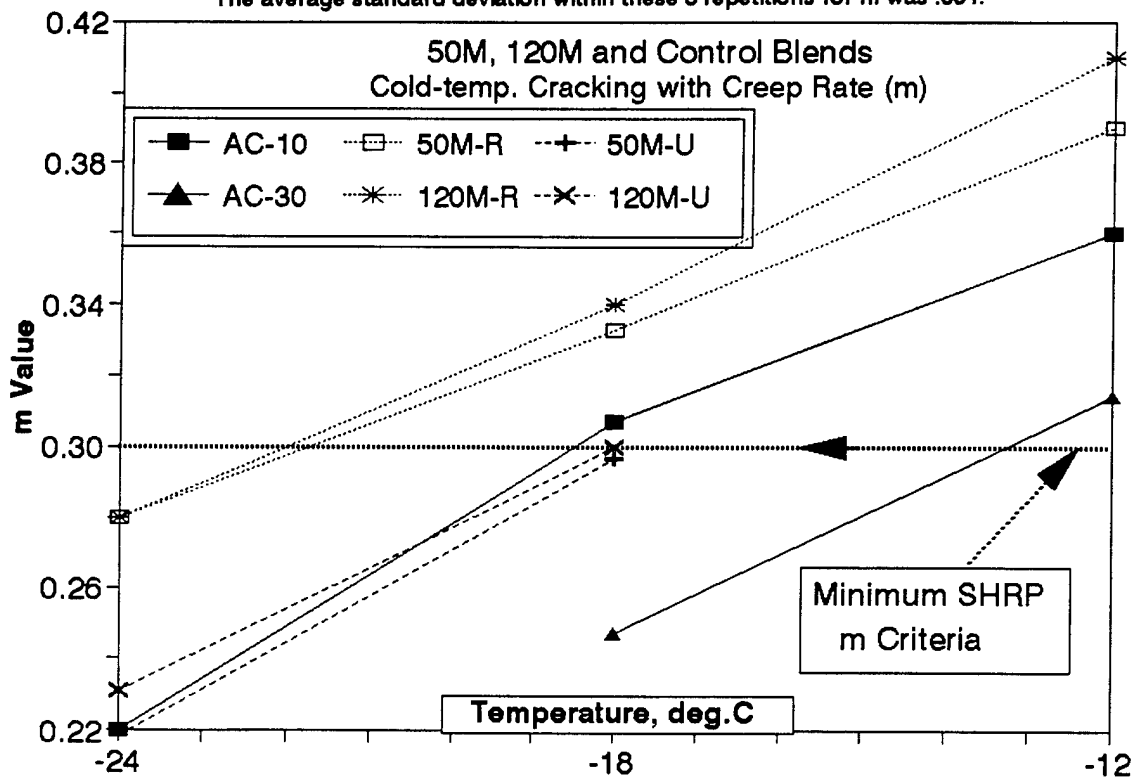


Figure 5.15 BBR Creep Rate (m) vs Temperature of All Blends

Table 5.5 Test Temperature Minimums at Which SUPERPAVE Criteria with BBR Were Met

| Blend | Minimum test temp. ($^{\circ}\text{C}$) at which Cold-temperature cracking criteria is met for the creep stiffness (S) criterion: $S \leq 300 \text{ MPa}$ | Minimum test temp. ($^{\circ}\text{C}$) at which Cold-temperature cracking criteria is met for the log. creep rate (m) criterion: $m \geq .30$ |
|---------|--|--|
| AC-10 | -19 | -18 |
| AC-30 | -14 | -13 |
| 16M-R | -25 | -20 |
| 40M-R | -24 | -21 |
| 50M-R | -25 | -22 |
| 120M-R | -25 | -22 |
| 16M-U | -23 | -18 |
| 40M-U | -22 | -18 |
| 50M-U | -23 | -18 |
| 120M-U | -22 | -18 |
| 50M-TFO | -25 | -19 |

As Table 5.5 indicates, the same relative performance of the groups exist as was discussed when analyzing the -18°C S and m data. What this table provides, however, is a better perspective of how much benefit there is with the addition of reacted and unreacted CRM. For instance, in terms of S , the 16M-R blend should theoretically have the same minimally acceptable performance at 11°C colder temperature than the AC-30, while the 16M-U blend would have the same at 9°C colder temperature than the AC-30.

"QUASI" SUPERPAVE GRADE

Tables 5.1 and 5.5 summarized for each blend the extreme temperatures at which the minimum SUPERPAVE performance criteria were met. Using these extreme temperatures, "quasi" SUPERPAVE grades for each of the 10 test blends are listed in Table 5.6 using the rutting criterion for the high temperature end, which was more critical than the tenderness criterion, and using the m parameter on the cold-temperature end, which was more critical than the S parameter. The difference between the high and low temperature grades is shown in the last column of Table 5.6, which reflects the temperature range at which the SUPERPAVE criteria are met. The larger the range, the better the overall binder quality is.

Table 5.6 Summary of Binder Blends' Acceptable Temperature Performance Range

| Blend | "quasi" SUPERPAVE grade using rutting and m -value parameters which controlled | Temperature range which meets criteria |
|--------|---|---|
| AC-10 | 58-28 | 86 |
| AC-30 | 64-23 | 87 |
| 16M-R | 70-30 | 100 |
| 40M-R | 68-31 | 99 |
| 50M-R | 68-32 | 100 |
| 120M-R | 69-32 | 101 |
| 16M-U | 66-28 | 94 |
| 40M-U | 65-28 | 93 |
| 50M-U | 65-28 | 93 |
| 120M-U | 68-28 | 96 |

The reacted blends have 12 to 15 °C more range than the two control asphalts, which had almost identical ranges. The unreacted blends have 6 to 10 °C more range

than the two control asphalts. These "quasi" grades do not even consider the results of the S parameter, which showed an even larger benefit from both reacted and unreacted CRM than the m parameter results. This "quasi" grading system also does not utilize the results of the fatigue parameter, which also showed the presence of reacted and unreacted CRM to be of significant benefit.

CHAPTER VI. PHASE II TEST RESULTS AND ANALYSIS

This chapter is divided into five main sections to present and analyze the results of Phase II. The first section discusses the results of the independent mix designs performed for each of the five mixes. The second section presents and analyzes all RM testing. Along with comparing the RM values themselves, LT aging and temperature susceptibility are examined using RM values. The third section studies the results of the IT tests, both the ITS and ϵ_f . The fourth section covers the creep test results. The fifth section summarizes the statistical contrasts made between: the CRM mixes versus the CNTRL mix, the wet versus dry process mixes, and finally the 16M versus 80M mixes. These contrasts are performed using the parameters discussed in the first four sections.

All the individual sample test results are tabulated in the Appendices. Appendix D covers all RM results while Appendix E covers both the IT and Creep results. A brief explanation of the tables is at the front of each appendix.

MIX DESIGNS

Before discussing the optimum binder content selected to achieve 4% VTM with each mix, the specific gravities for each of the mix components used in the designs will be discussed. Other mix specifics, such as aggregate type and gradation, were discussed in Chapter III.

Specific Gravity of Mix Components

The bulk specific gravity (SG) of the aggregate blend was determined to be 2.810 using ASTM's C127 and C128. The effective SG of the aggregate was determined separately for each mix using ASTM D2041 (Rice test). Three Rice samples were tested per mix and an effective SG calculated from each test, then an average taken and used for each mix design. These are illustrated in Table 6.1. The exception was the 16M Wet mix in which 7 samples were tested because of the unusually high values obtained. Various alternative procedures were tried including the dry-back procedure and using buttered trays, but the high results continued, so the average of all seven tests was used.

Table 6.1 Effective Specific Gravity of Aggregate Determined for Each Mix

| Sample | CNTRL | 16M Wet | 16M Dry | 80M Wet | 80M Dry |
|---------|-------|---------|---------|---------|---------|
| 1 | 2.861 | 2.881 | 2.862 | 2.861 | 2.855 |
| 2 | 2.858 | 2.883 | 2.868 | 2.857 | 2.862 |
| 3 | 2.865 | 2.875 | 2.865 | 2.861 | 2.863 |
| 4 | | 2.870 | | | |
| 5 | | 2.873 | | | |
| 6 | | 2.866 | | | |
| 7 | | 2.869 | | | |
| Average | 2.862 | 2.875 | 2.865 | 2.860 | 2.860 |

The binder SG for the AC-30 and the wet mix's CRM/AC-10 blends were determined using ASTM D70. Both dry mixes were assumed to have a CRM/AC-10 blend with the same SG as their corresponding wet mix's CRM/AC-10 blend. The average SG values obtained from several tests were used for the mix designs and were: 1.033 for the AC-30, 1.039 for the 16MCRM/AC-10 blends, and 1.044 for the 80MCRM/AC-10 blends. The producers of the CRM and AC-10 report SGs of 1.15

and 1.025 respectively, resulting in a theoretical SG of the blend (using 15% CRM) of 1.040, which is very close to the values used.

Optimum Binder Content Selection

An optimum binder content was selected for each mix to produce samples with 4% VTM. The bulk SG of each mix sample was determined using ASTM 2726 while the theoretical maximum SG at each trial binder content was calculated using the effective SGs in Table 6.1. From the bulk and theoretical maximum SGs, the VTM for each sample was calculated. As discussed in Chapter III, three samples were prepared at either 4 or 5 trial binder contents for each mix design. The VTM in relation to trial binder content is plotted for the CNTRL and 16M Wet mix designs in Figure 6.1, while the other three designs are shown in Figures 6.2, 6.3 and 6.4. As is standard procedure for mix designs, a best fit curve is hand drawn for each design and then the optimum binder content is selected. These five optimums are summarized in Table 6.2. The VMA for the samples at optimum (3 to 5% VTM) was generally 12.5 to 14.5%, lower than originally desired, but acceptable. The VFA for these samples was generally 68 to 76%.

Table 6.2 Optimum Binder Contents from Independent Mix Designs

| Mix | Optimum Binder Content, % ($W_{t_{CRM \text{ and } AC}} / W_{t_{mix}}$) |
|---------|--|
| CNTRL | 4.1 |
| 16M Wet | 5.0 |
| 16M Dry | 5.0 |
| 80M Wet | 4.4 |
| 80M Dry | 4.4 |

Note the optimums of the wet and dry mixes are identical for not only the 16M CRM, but also the 80M CRM. This indicates the wet and dry mixes are compacting identically. One possible reason the 16M mixes have a higher optimum than the 80M mixes is the larger CRM particles provide more rebound during compaction. This may produce more voids in the aggregate structure (VMA) and thus require more AR to produce 4% VTM.

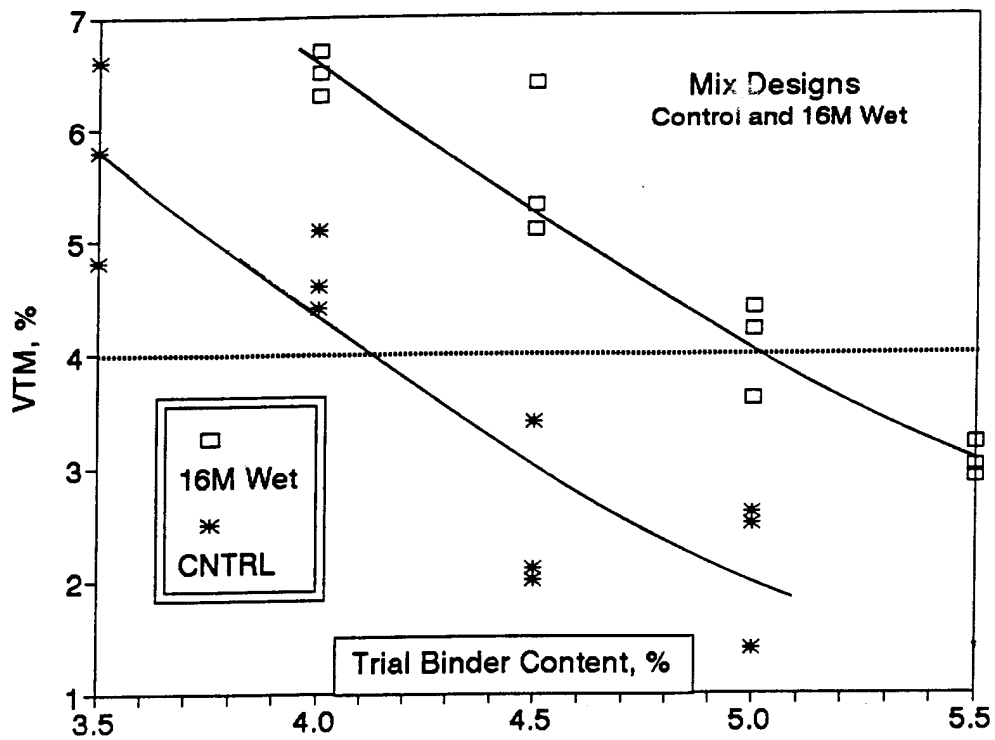


Figure 6.1 VTM vs Trial Binder Content for CNTRL and 16M Wet Mix Designs

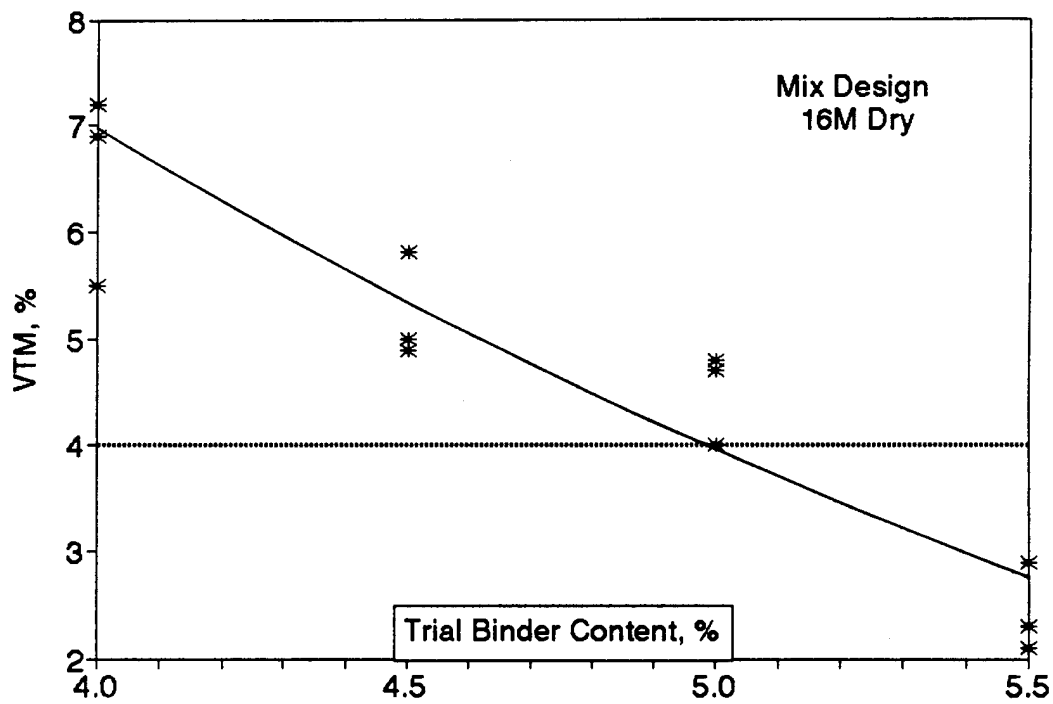


Figure 6.2 VTM vs Trial Binder Content for 16M Dry Mix Design

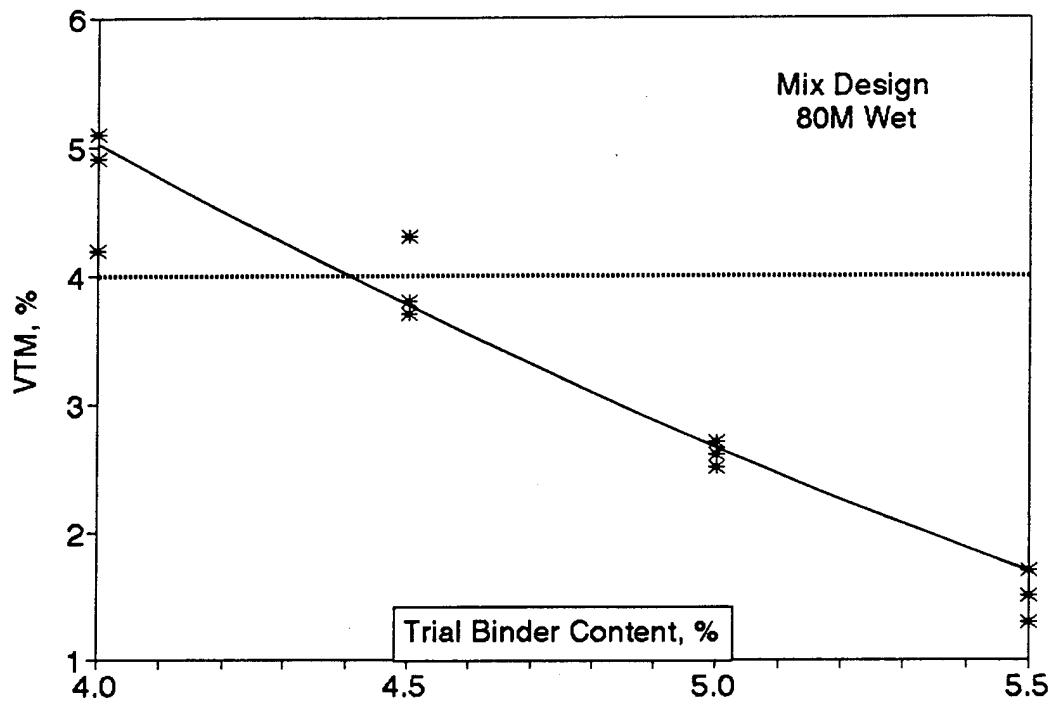


Figure 6.3 VTM vs Trial Binder Content for 80M Wet Mix Design

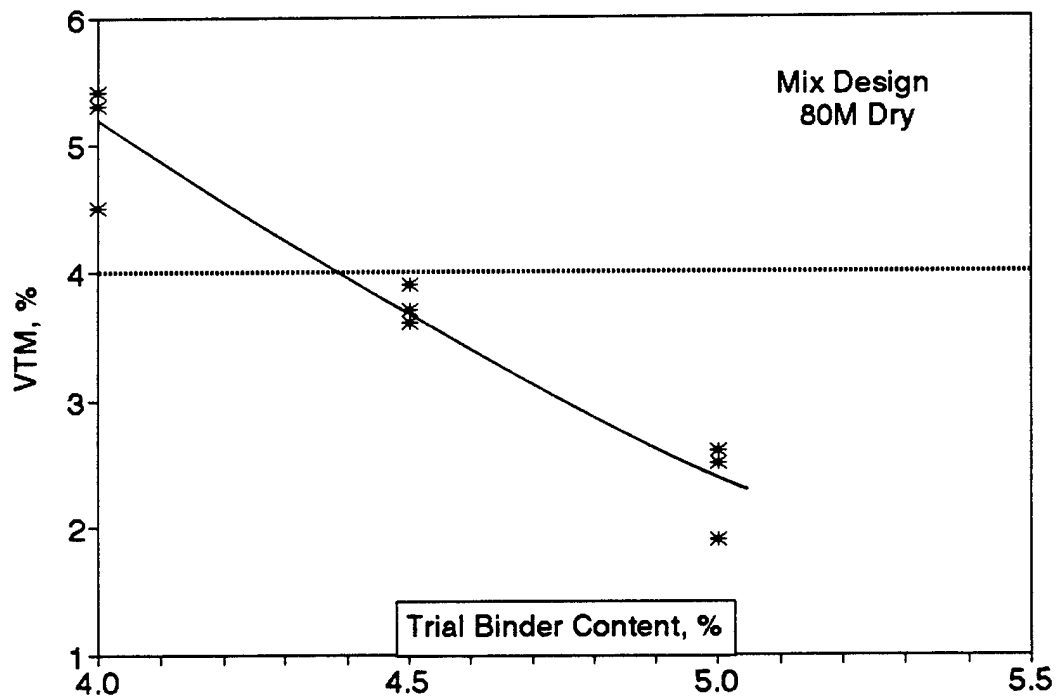


Figure 6.4 VTM vs Trial Binder Content for 80M Dry Mix Design

RM TESTS

RM Values at Each Temperature

Average corrected (corrected to 15% ITS) RM values at 40, 25 and 5 °C are presented in Tables 6.3, 6.4 and 6.5, respectively. Results include two categories of samples: "the 4% VTM samples" and the "7% VTM samples before LT aging." The averages for the "7% VTM samples after LT aging" were not included because they would have put an undesired bias into the statistical analysis performed, since the 7% VTM samples would have been tested twice and the 4% VTM samples only once. Complete results are tabulated in Appendix D.

The statistical procedure used to compare the five mixes in Tables 6.3 through 6.5 and several forthcoming tables was a Student-Newman-Keuls multiple comparison test. This comparison test method was selected over others because statisticians recommend it when there is a control in the group of treatments (66). If any two mixes have significantly different overall average RM values, they will not have the same letter in the last column of the table. The probability level of the test was 5%. The statistical model included the mix, the category (4% versus 7% VTM), and any interaction between mix and category. This meant the error term used for the comparisons was based strictly on the variability within the three sample repetitions. The degrees of freedom for the error term (DFE) and the mean square of the error (MSE) are listed on each table as well as the Coefficient of Variability within the sample repetition (CV).

Table 6.3 Average RM Values at 40°C

| Mix | Averages of Corrected (to 15% ITS) Resilient Mod. @ 40°C, MPa x 10 ³ | | Overall Average of 6 samples | Multiple Comparison Grouping (see Note) |
|---|--|---|------------------------------------|--|
| | 4% VTM (3 samples) | 7% VTM (before LT aging) (3 samples) | | |
| CNTRL | 1.197 | 0.942 | 1.069 | A |
| 16M Wet | 0.816 | 0.647 | 0.731 | B |
| 16M Dry | 0.730 | 0.703 | 0.717 | B |
| 80M Wet | 0.784 | 0.671 | 0.728 | B |
| 80M Dry | 0.852 | 0.670 | 0.761 | B |
| Note: Mixes with the same letter do not have significantly different overall averages (probability level = 5%). DFE = 20, MSE = 3380, CV = 7.3% | | | | |

Table 6.4 Average RM Values at 25°C

| Mix | Averages of Corrected (to 15% ITS) Resilient Mod. @ 25°C, MPa x 10 ³ | | Overall Average of 6 samples | Multiple Comparison Grouping (see Note) |
|---|--|---|------------------------------------|--|
| | 4% VTM (3 samples) | 7% VTM (before LT aging) (3 samples) | | |
| CNTRL | 4.31 | 3.18 | 3.74 | A |
| 16M Wet | 2.87 | 1.37 | 2.12 | B |
| 16M Dry | 2.45 | 1.57 | 2.01 | B |
| 80M Wet | 1.93 | 1.64 | 1.78 | B |
| 80M Dry | 2.69 | 1.33 | 2.01 | B |
| Note: Mixes with the same letter do not have significantly different overall averages (probability level = 5%). DFE = 20, MSE = .06285, CV = 10.7%. | | | | |

Table 6.5 Average RM Values at 5 °C

| Mix | Averages of Corrected (to 15% ITS) Resilient Mod. @ 5 °C, MPa x 10 ³ | | Overall Average of 6 samples | Multiple Comparison Grouping (see Note) |
|--|--|---|------------------------------------|--|
| | 4% VTM (3 samples) | 7% VTM (before LT aging) (3 samples) | | |
| CNTRL | 29.4 | 28.6 | 29.0 | A |
| 16M Wet | 17.6 | 16.7 | 17.1 | B |
| 16M Dry | 16.6 | 14.4 | 15.5 | B |
| 80M Wet | 18.4 | 15.5 | 16.9 | B |
| 80M Dry | 20.6 | 15.6 | 18.1 | B |
| Note: Mixes with the same letter do not have significantly different overall averages (probability level = 5%). DFE = 20, MSE = 5.856, CV = 12.5%. | | | | |

As Tables 6.3, 6.4 and 6.5 show, there is no significant difference between any of the four CRM mixes at any of the three test temperatures. The CNTRL mix, however, does have a significantly higher RM value compared to the CRM mixes at all three temperatures and for both categories. The trend for the CNTRL to be substantially stiffer than the other CRM mixes is consistent at all three temperatures. This was expected based on the binder tests in Phase I which showed the AC-30 to have a substantially higher G^* than the CRM blends between 10 and 28 °C. If one were to use the AASHTO design guide to select a surface structural layer coefficient (which is based on RM @ 20 °C), the thickness of a CRM mix would have to be increased 25% over that of the CNTRL mix to provide the same structural capacity. It is important to note that there appears to be no difference between the wet and dry mixes or the 16M and 80M mixes, although this will be analyzed closer with a more effective statistical procedure using contrasts at the end of this chapter.

Aging

The average aging ratios calculated as $RM_{\text{after LT aging}} / RM_{\text{before LT aging}}$ for each mix and at each temperature, are displayed in Table 6.6. These averages are calculated from the individual sample ratios listed in Table D.4. The standard deviations among each of these mix categories are also calculated to provide an indication of variability. An average ratio across the three temperatures, which is actually an average of 9 samples, is shown in the last column. The overall CV within the sample repetition, calculated from a pooled variance, is noted at the bottom.

Table 6.6 LT Aging Ratios (averages and standard deviations) in terms of RM

| Mix | Aging Ratios ($RM_{\text{after LT aging}} / RM_{\text{before LT aging}}$) | | | | | | Average Ratio from Three Temperatures |
|---------|---|-----|-----------------------|-----|----------------------|-----|---------------------------------------|
| | @ 40°C (3 samples) | | @ 25°C (3 samples) | | @ 5°C (3 samples) | | |
| | Avg. | s | Avg. | s | Avg. | s | |
| CNTRL | 1.14 | .14 | 1.32 | .10 | 0.93 | .12 | 1.13 |
| 16M Wet | 1.13 | .06 | 1.48 | .20 | 0.84 | .17 | 1.15 |
| 16M Dry | 0.91 | .06 | 1.08 | .04 | 0.95 | .09 | .98 |
| 80M Wet | 1.13 | .09 | 1.14 | .05 | 1.11 | .29 | 1.13 |
| 80M Dry | 1.16 | .10 | 1.53 | .18 | 1.06 | .04 | 1.25 |
| | CV = 11.8%, DFE = 30, MSE = .0179 | | | | | | |

As shown, the ratios are fairly close to 1.0, meaning the mixes did not stiffen substantially due to aging. The RM values had an overall average increase of only 13%, which is small when compared to the overall CV of 12%. Based on the large CV and small average aging ratios, a comparison of aging characteristics between the mixes would be inconclusive. The low ratios do suggest, however, the SUPERPAVE LT aging procedure (5 days at 85°C), assuming it was performed properly in this

project, may not be harsh enough to provide significant aging to gap-graded mixes in terms of RM. An explanation may be that a gap-graded mix will typically have a thicker average asphalt film than dense-graded mixes, and dense-graded mixes were likely used when developing these LT aging procedures.

Temperature Susceptibility

The relationship between log mix stiffness and temperature is believed to be generally linear. The average corrected RM values (already presented in Tables 6.3, 6.4 and 6.5) are plotted on log scale versus the three testing temperature in Figures 6.5 and 6.6. Figure 6.5 uses the "4% VTM" averages while Figure 6.6 uses the "7% VTM before LT aging" averages. The "7% VTM after LT aging" corrected RM averages are used in Figure 6.7.

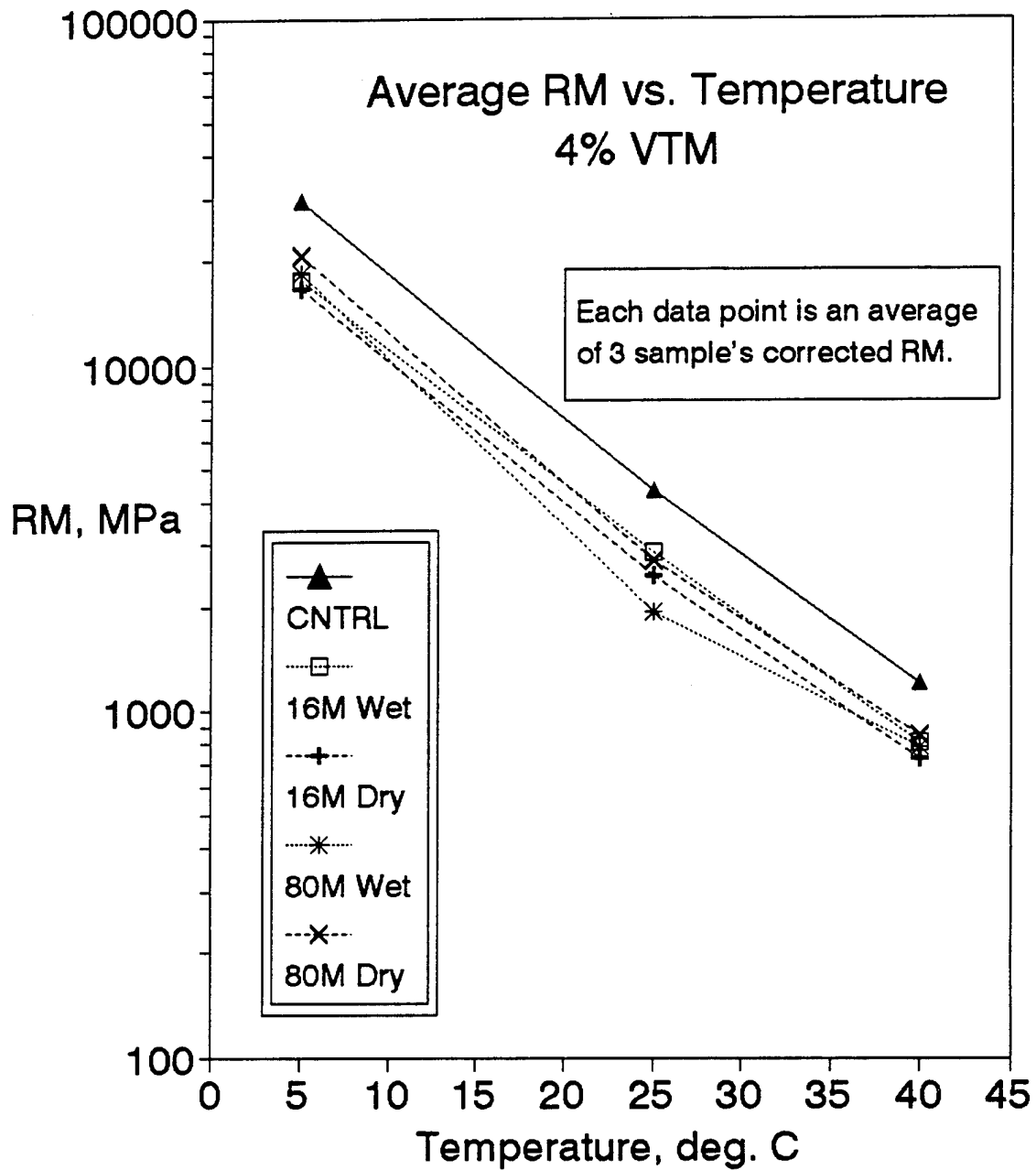


Figure 6.5 Average RM vs Temperature for 4% VTM Samples

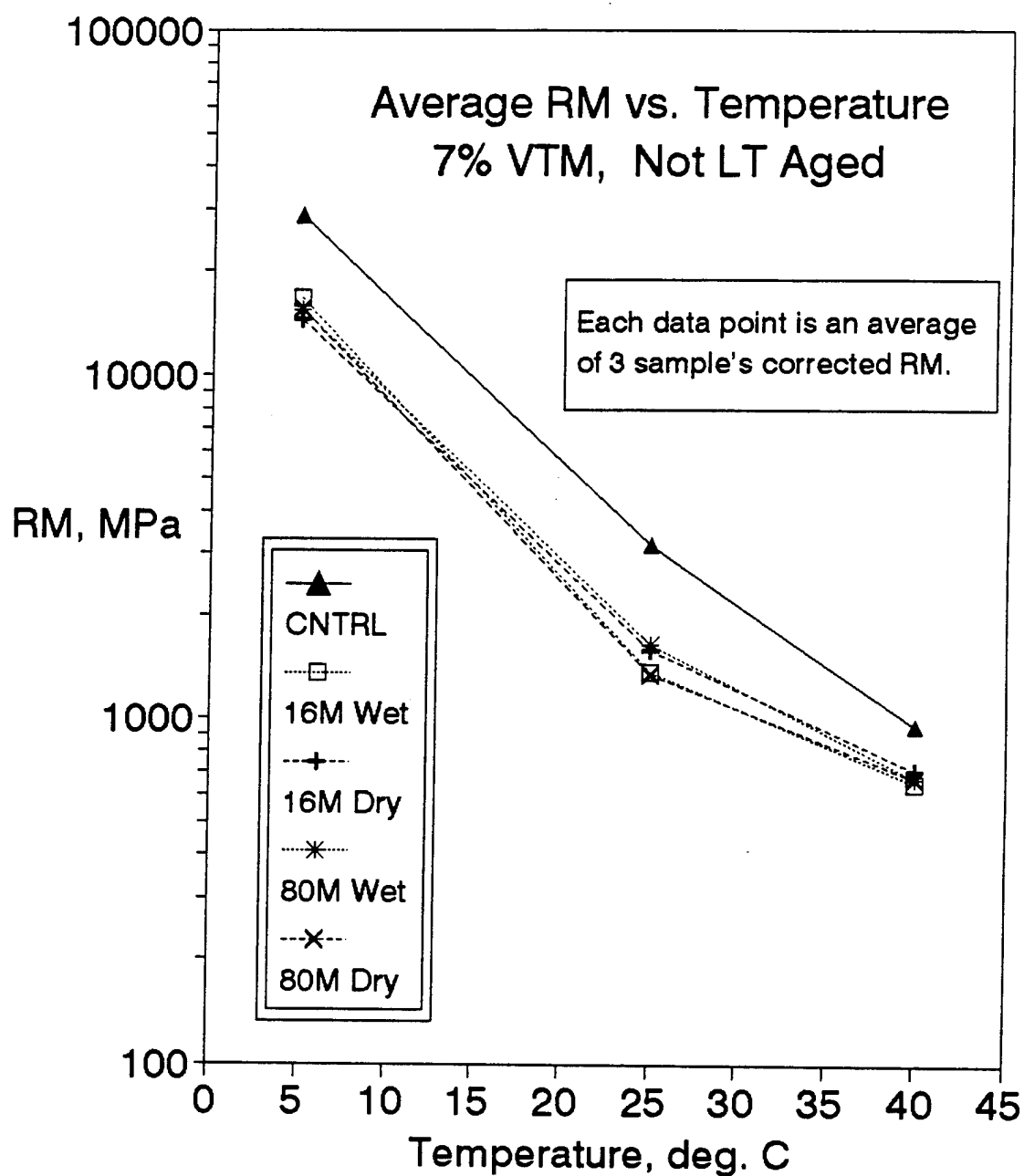


Figure 6.6 Average RM vs Temperature for 7% VTM Samples Before LT Aging

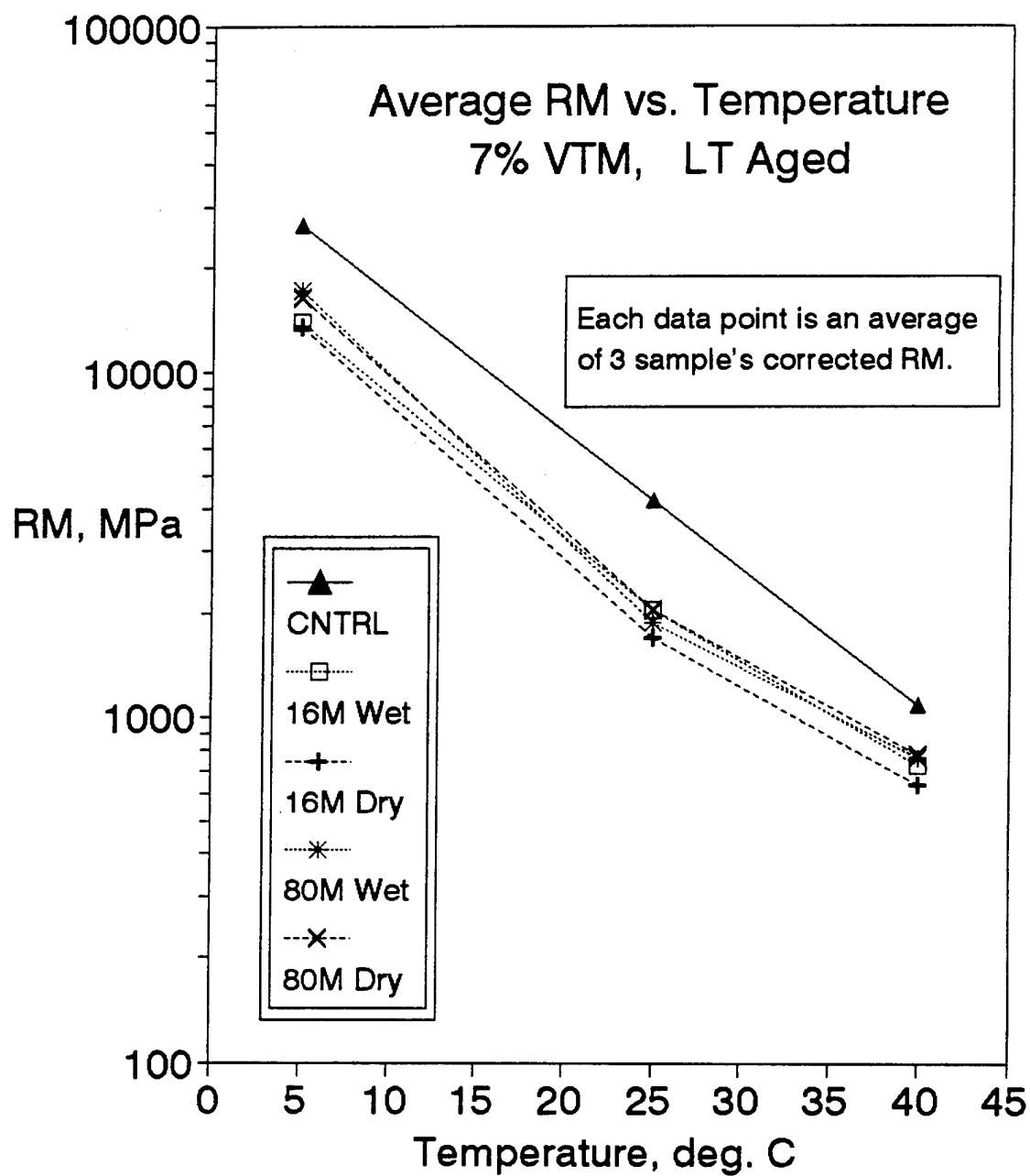


Figure 6.7 Average RM vs Temperature for 7% VTM Samples After LT Aging

The lines which connect the three points for each of the five mixes on Figures 6.5 through 6.7 appear to have a trend of upward curvature. On Figures 6.6 and 6.7, the slopes of the lines for the four CRM mixes between 25 and 40°C certainly appear to be less than the slope of the CNTRL mix. A smaller slope indicates less temperature susceptibility.

Since \log_{10} RM versus temperature plots are generally thought to be linear and to obtain an objective measure of temperature susceptibility, linear regression was used for each set of points (each mix) in Figures 6.5, 6.6 and 6.7. The slopes of these best-fit lines are listed in Table 6.7 and are all based on nine data points (three RM values at three temperatures). The last column is simply an average slope from the three categories. Table 6.8 is identical to Table 6.7, but the uncorrected RM values (which were not plotted) were used for regression instead of the corrected RM values.

It is not surprising there is only a small difference between these slope values when you look at Figures 6.5, 6.6 and 6.7 and try to draw a best fit line through the three points. The fact the relationship between \log_{10} RM vs temperature does not appear to be exactly linear detracts from this analysis. Even though no statistical comparison was performed on these slope values, it is interesting to note that for all three categories on both Tables 6.7 and 6.8, the CNTRL mix had the steepest slope, indicating a general trend that the CNTRL mix is more susceptible to temperature than the CRM mixes. By looking at the Figures 6.6 through 6.8 though, one would likely quantify this statement by saying the CRM mixes appeared less temperature sensitive only between 25 and 40°C. Once again, there was no apparent differences in the trends between the wet and the dry process mixes or between the 16M and the 80M CRM mixes.

Table 6.7 Regression Slopes of Corrected log RM vs Temperature Plots

| Mix | Slopes of Avg. Corrected log RM (MPa) vs Temp ($^{\circ}$ C), $\times 10^{-2}$ | | | Average Slope from the Three Sample Categories |
|---------|--|--------------------------------------|----------------------------------|---|
| | 4% VTM (3 samples) | 7% VTM Not LT Aged (3 samples) | 7% VTM LT Aged (3 samples) | |
| CNTRL | 3.982 | 4.262 | 3.983 | 4.076 |
| 16M Wet | 3.820 | 4.105 | 3.698 | 3.875 |
| 16M Dry | 3.891 | 3.805 | 3.837 | 3.845 |
| 80M Wet | 3.967 | 3.950 | 3.922 | 3.946 |
| 80M Dry | 3.975 | 3.982 | 3.833 | 3.930 |

Table 6.8 Regression Slopes of Uncorrected log RM vs Temperature Plots

| Mix | Slopes of Avg. Uncorrected log RM (MPa) vs Temp ($^{\circ}$ C), $\times 10^{-2}$ | | | Average Slope from the Three Sample Categories |
|---------|--|--------------------------------------|----------------------------------|---|
| | 4% VTM (3 samples) | 7% VTM Not LT Aged (3 samples) | 7% VTM LT Aged (3 samples) | |
| CNTRL | 3.953 | 4.270 | 3.941 | 4.055 |
| 16M Wet | 3.727 | 4.123 | 3.653 | 3.834 |
| 16M Dry | 3.758 | 3.883 | 3.697 | 3.779 |
| 80M Wet | 3.842 | 3.946 | 3.797 | 3.862 |
| 80M Dry | 3.825 | 3.986 | 3.708 | 3.840 |

IT TESTS

Average ITS values at 25 °C are presented in Table 6.9. The results of all individual IT tests are in Appendix E. The same multiple comparison procedure as performed with the RM values is used here. The multiple comparison groupings are indicated in the last column for the overall averages of each mix (in the next to last column). There are four categories of samples for the IT tests. They are: "4% VTM samples before RM testing" (only 1 repetition), "4% VTM samples after RM testing", "7% VTM samples before LT aging" and "7% VTM samples after LT aging." The 4% VTM samples were separated into two categories because they were broken at two different times, with two months transpiring from when the first set was tested in IT (before any RM testing) till when the next set was tested in IT (after being RM tested). A 20% average increase in ITS was observed due to the samples stiffening over these two months. By separating these two categories, the error term used in the statistical analysis was minimized. The "7% VTM samples after LT aging" were tested in IT also two months after the "7% VTM samples before LT aging" were tested. The average increase in ITS was 43% for the "after LT aging" mixes compared to the "before LT aging" mixes.

Table 6.9 Average ITS Results @ 25 °C

| Mix | Avg. IT Peak Stress (ITS), MPa | | | | Overall Avg. of 10 samples | Multiple Compar. Grouping (see Note) |
|--|--------------------------------|---------------------|---------------------------|---------------------------|----------------------------|--------------------------------------|
| | 4% VTM | 4% VTM | 7% VTM | 7% VTM | | |
| | bef. RM 1 smpl. | aft. RM 3 smpls. | bef. LT Aging 3 smpls. | aft. LT Aging 3 smpls. | | |
| CNTRL | 2.02 | 2.28 | 1.44 | 1.91 | 1.89 | A |
| 16M Wet | 1.14 | 1.35 | 0.89 | 1.20 | 1.15 | C |
| 16M Dry | 1.13 | 1.43 | 0.76 | 1.11 | 1.10 | C |
| 80M Wet | 1.29 | 1.49 | 0.96 | 1.39 | 1.28 | B |
| 80M Dry | 1.19 | 1.56 | 0.94 | 1.38 | 1.28 | B |
| Note: Mixes with the same letter do not have significantly different overall averages with SNK test (probability level = 5%). DFE = 30, MSE = .005089, CV = 5.3%. | | | | | | |

As Table 6.9 shows, the CNTRL mix had significantly higher average ITS values than the four CRM mixes in all categories. The 80M mixes also had significantly higher ITS values than the 16M mixes. The difference between the CNTRL and CRM mixes is much larger than the difference between the 16M and 80M mixes. Note once again there is no significant difference between the wet and dry mixes for either the 16M or the 80M CRM size, even though the error term used was small with a CV of 5.3%.

The high ITS values for the CNTRL mix was expected since Phase I showed a higher G^* for the AC-30 at 25 °C compared to the CRM blends, and since the RM tests confirmed the CNTRL was stiffer than the CRM mixes. Generally, a stiffer binder and/or stiffer mix will result in a higher ITS. Also, as the binder content

increases for a mix, the ITS will generally decrease. Differences in binder content may then explain why the CNTRL mix had the highest ITS (4.1% AC), followed by the 80M mixes (4.4%AR), and the 16M mixes had the lowest ITS (5.0% AR).

Table 6.10 reports the ϵ_f % using the same format as Table 6.9. Mixes which can tolerate a higher strain prior to failure are more likely to resist low-temperature cracking than mixes with low ϵ_f % (35).

Table 6.10 Average IT ϵ_f Results @ 25°C

| Mix | Avg. IT Strain @ Failure (ϵ_f), % | | | | Overall Avg. of 10 samples | Multiple Compar. Grouping (see Note) |
|--|--|----------------------------|----------------------------------|----------------------------------|----------------------------|--------------------------------------|
| | 4% VTM bef. RM 1 smpl. | 4% VTM aft. RM 3 smpls. | 7% VTM bef. LT Aging 3 smpls. | 7% VTM aft. LT Aging 3 smpls. | | |
| CNTRL | .68 | .69 | .71 | .86 | .75 | A |
| 16M Wet | .59 | .69 | .77 | .77 | .73 | A |
| 16M Dry | .63 | .63 | .87 | .81 | .76 | A |
| 80M Wet | .59 | .63 | .68 | .69 | .66 | B |
| 80M Dry | .59 | .63 | .68 | .60 | .63 | B |
| Note: Mixes with the same letter do not have significantly different overall averages with SNK test (probability level = 5%). DFE = 30, MSE = .002020, CV = 6.4%. | | | | | | |

From the multiple comparison tests, the average ϵ_f values for the 16M Wet, 16M Dry and CNTRL mixes did not differ. The average ϵ_f values for the 80M Wet and 80M Dry mixes also did not differ. Thus, the process (wet or dry) did not effect ϵ_f , but the CRM size did. The results indicate the 80M mixes should have worse low-temperature cracking performance than the other mixes.

CREEP TESTS

The average permanent $\epsilon\%$ values from creep tests are reported in Table 6.11. The individual creep test results are in Appendix E. There are two categories of samples, those prepared at optimum binder content and those at approximately $\frac{1}{2}\%$ over optimum. The word "approximately" is used because the samples which were available from the mix designs were not exactly $\frac{1}{2}\%$ over optimum. Rather, the CNTRL samples were .4% over optimum, the 16M Wet and 16M Dry samples were .5% over, and the 80M Wet and 80M Dry samples were .6% over.

Table 6.11 Average Creep Results @ 60°C

| Mix | Permanent ϵ , % | | | |
|---------|---|--|--|--|
| | Binder % is @ Optimum (3 samples) | | Binder % is approx. $\frac{1}{2}\%$ over Optimum (3 samples) | |
| | Avg. | Multiple Comparison Grouping (see Note) | Avg. | Multiple Comparison Grouping (see Note) |
| CNTRL | 1.43 | A | 2.20 | A |
| 16M Wet | 2.48 | A | 2.03 | A |
| 16M Dry | 1.59 | A | 2.90 | A |
| 80M Wet | 1.93 | A | 1.87 | A |
| 80M Dry | 1.42 | A | 2.22 | A |
| | DFE = 10, MSE = .3914, CV = 35.3% | | DFE = 10, MSE = .2884, CV = 23.9% | |
| | Note: Mixes with the same letter do not have significantly different overall averages (prob. level = 5%) | | | |

All the permanent ϵ averages are relatively low, indicating all the mixes were stable, even at $\frac{1}{2}\%$ over optimum. There is no significant difference between any of

the mixes during the multiple comparison for either category. The variability of this test was much higher than the other tests, with the CV of each category being 35.3% and 23.9% respectively.

STATISTICAL CONTRASTS

In addition to comparing the mixes through multiple comparison tests, an additional type of statistical comparison was performed called contrasts. Contrasts make direct comparisons between the one CNTRL versus the four CRM mixes, the two wet versus the two dry process mixes, and the two 16M versus the two 80M CRM mixes, using the previously reported test variables. Each of the two groups are averaged and compared to determine if they are significantly different (probability level = 5%). These contrasts show if there is a significant effect from: the presence of CRM, the process of adding CRM, and the CRM particle size, respectively. The interaction between the process and CRM particle size was also tested for significance. Table 6.12 summarizes these contrasts. As the Note column annotates, the sample categories used for these contrasts were the same as used during the previous analysis of each measured variable.

This additional statistical analysis provides a different view of the same data, and offers the same conclusions made earlier with the multiple comparison tests. First, there is no significant difference between the wet and dry mixes for any of the variables. Second, the CNTRL has significantly higher RM, ITS and ϵ_f values than the CRM mixes. Third, only the ITS and ϵ_f variables show a significant difference between the 16M and 80M mixes. Lastly, the creep data provided no significant differences with any of the three contrasts. Not previously tested, the interaction between the process and CRM size was not significant for any variables.

Table 6.12 Contrasts between CRM vs No CRM Mixes, Wet vs Dry Mixes, and 16M vs 80M Mixes

| Each Contrast was either Significantly Different (SD) or Not SD, (probability level = 5%) | | | | | |
|---|------|---------------------------|------------------------|-------------------------|---|
| Variable | Note | CNTRL vs CRM Mixes | Wet vs Dry Mixes | 16M vs 80M Mixes | Interaction between Process and CRM Size |
| RM @ 40°C | * | SD (CNTRL higher) | Not SD | Not SD | Not SD |
| RM @ 25°C | * | SD (CNTRL higher) | Not SD | Not SD | Not SD |
| RM @ 5°C | * | SD (CNTRL higher) | Not SD | Not SD | Not SD |
| ITS | # | SD (CNTRL ✓ higher) | Not SD ✓ | SD (80M ✓ higher) | Not SD |
| IT ϵ_f | # | SD (CNTRL ✓ higher) | Not SD ✓ | SD (16M ✓ higher) | Not SD |
| Creep @ Opt AC% | & | Not SD | Not SD | Not SD | Not SD |
| Creep @ .5% over Opt AC% | & | Not SD | Not SD | Not SD | Not SD |
| Notes: * - used the same two sample categories as used in Tables 6.2, 6.3 and 6.4. # - used all four sample categories as used in Tables 6.8 and 6.9. & - used the one sample category as described in the Variable column. | | | | | |

CHAPTER VII. CONCLUSIONS AND RECOMMENDATIONS

PHASE I CONCLUSIONS

Phase I demonstrated the addition of both fully reacted and unreacted CRM improves predicted binder performance using the SUPERPAVE tests and criteria. Since the unreacted blends (U) establish the "worst case" binder modification by the dry process while the reacted blends (R) establish the "best case", one can assume the true binder modification associated by adding the CRM dry is somewhere between the unreacted and the reacted blends. Generally, the reacted blends outperformed the unreacted blends, while both outperformed the control blends.

The SUPERPAVE grading system uses increments of 6°C to distinguish between grades, both on the high and low temperature ends. This 6°C incrementing of grades is used in the following statements to summarize the effects of both reacted and unreacted CRM.

1) For tenderness and rutting, the reacted blends (with an AC-10 base) were approximately 1 SUPERPAVE grade better than the AC-30 and 2 grades better than the AC-10. The unreacted blends (also with an AC-10 base) were approximately $\frac{1}{2}$ grade better than the AC-30 and $1\frac{1}{2}$ grades better than the AC-10.

2) For fatigue, the reacted blends were approximately 1 grade better than the AC-10 and 2 grades better than the AC-30. The unreacted blends were approximately $\frac{1}{2}$ grade better than the AC-10 and $1\frac{1}{2}$ grades better than the AC-30.

3) For cold-temperature cracking with the S parameter, the reacted blends were approximately 1 grade better than the AC-10 and 2 grades better than the AC-

30. The unreacted blends were approximately $\frac{1}{2}$ grade better than the AC-10 and $1\frac{1}{2}$ grades better than the AC-30.

4) For cold-temperature cracking with the m parameter, the reacted blends were approximately $\frac{1}{2}$ grade better than the AC-10 and $1\frac{1}{2}$ grades better than the AC-30. The unreacted blends were approximately the same grade as the AC-10 and 1 grade better than the AC-30.

Other conclusions drawn from Phase I are as follows.

1) All reacted and unreacted blends had better "relative elasticity" (lower phase angle for the same stiffness) than the control blends at both high and low temperatures. This was demonstrated by plotting delta versus G^* for all blends. The two control blends (from the same source) had identical delta versus G^* relationships.

2) CRM size between 16M and 120M nominal maximum size had little influence on binder properties relative to the overall large effect from the presence of CRM.

3) The reacted blends aged slower in the TFO than the controls, suggesting the addition of CRM slows the binder aging process.

PHASE II CONCLUSIONS

The five mixes tested in Phase II were: 16M wet, 16M dry, 80M wet, 80M dry and a control. All mixes had the same limestone aggregate, gap-gradation and compatible AC source. The four CRM mixes had a constant CRM/AC-10 ratio of .15 while the control mix's binder was an AC-30 with no CRM. All mixes were short-term aged for 4 hours at 152 °C before compacting into samples. Comparisons were made between mixes of the wet versus dry process, 16M versus 80M CRM, and

CRM versus no CRM. The word "significant" is only used below when referring to statistically significant differences of test results.

Comparison of Wet and Dry Process: There was no difference between mixes when the CRM was added wet rather than being added dry. This is supported by the following.

- 1) From the independent mix designs performed on each mix, the 16M wet and 16M dry mixes each had identical optimum binder contents selected at 5.0% to achieve 4%VTM. The 80M wet and 80M dry each had identical optimums of 4.4%. The control mix had an optimum of 4.1%. These identical optimums indicate the wet and dry mixes are compacting identically. Since the same amount of CRM and AC-10 was in each of the wet and dry samples which had the same CRM size, the only difference between the wet and dry samples was how the CRM was added.
- 2) None of the measured lab properties, (RM at 5, 25 and 40 °C, ITS and ϵ_f from the indirect tensile test, and permanent ϵ from the dynamic creep test) were significantly different between the wet and dry mixes. Some significant differences were found between the 16M and 80M CRM mixes and between the control and CRM mixes.

Comparison of 16M and 80M CRM: There was no significant difference between the 16M and 80M CRM mixes for RM (at 5, 25 and 40 °C) and for permanent creep ϵ . The 16M CRM mixes did have significantly higher ϵ_f and significantly lower ITS compared to the 80M CRM mixes.

Comparison of CRM Mixes and Control Mix:

- 1) The control mix had significantly higher RM (at 5, 25, and 40 °C), ITS and ϵ_f values compared to the four CRM mixes, but the permanent creep ϵ values were not significantly different.

2) From regression analysis, the four CRM mixes had slightly smaller slopes than the control mix on all log RM versus temperature plots, indicating the CRM mixes tend to be less temperature sensitive.

Other: Assuming the SUPERPAVE long-term aging procedures were followed correctly (5 days at 85°C), they may not be harsh enough to provide significant aging to gap-graded samples in terms of RM. The average increase was only 13%.

RECOMMENDATIONS

The following recommendations are based on this research, which was a limited lab study using tests which are believed to be predictors of performance. Only one CRM source and one compatible AC source were used. Also one aggregate type and one gap-gradation were used. The CRM/AC-10 weight ratio of .15 used for both the wet and dry mixes equated to a CRM/aggregate weight ratio of .61 for both 80M mixes and .69 for both 16M mixes. The short-term aging of the loose mixes was controlled at 152°C for four hours.

From Phase I results, both the wet and dry processes are warranted to modify a compatible AC with ground CRM sized at 16M and smaller.

From Phase I and Phase II results and knowing modification costs are less for the dry versus wet process, the dry process is recommended (versus the wet) if a low concentration of CRM finer than 16M is to be added to a gap-graded mix. Performance should be about the same with either process.

Test sections should be constructed in the field which not only use the dry process to add fine CRM, but also take wet process test sections and compare them to comparable test sections where the same type and amount of CRM is added dry. Comparisons between "wet" and "dry" could then be made based on field

performance. The suggested CRM size for this type of test section is 16M or finer. Since a few states have already had success with adding CRM "dry" sized between 40M to 80M, these sizes would be the safest to try, although costlier than 16M. Concerns with using larger CRM sizes are: 1) the storage time and temperature of the loose mix in the field may not be as high as in this project, making it more difficult for the larger CRM particles to completely react with the AC coating the aggregate and 2) larger CRM particles may bridge the aggregate, especially if the gradation is not as gap-graded as in this project.

Additional lab mix testing is also needed to better understand the quantity of binder modification which occurs when fine CRM is added dry and the loose mix is stored temporarily, as with short-term aging. The necessary time and temperature of short-term aging which allows the fine CRM, when added dry, to be fully reacted needs to be determined. This project suggests 4 hours at 152° C was sufficient for 80M and 16M CRM. Mixing time for this project was 2 to 2½ minutes, but this also is a variable which could be studied and extended in the field if determined to be of benefit.

REFERENCES

1. Terrel, R.L. and Epps, J.A., Using Additives and Modifiers in Hot Mix Asphalt - Part A and Modifier Groups - Part B, National Asphalt Pavement Association Quality Improvement Series 114A, Riverdale, MD., 1989.
2. Bloomquist, D., Diamond, G., Odin, M., Ruth, B., and Tia, M., Engineering Aspects of Recycled Materials for Highway Construction, Final Report, Western Research Institute for U.S. DOT, FHWA, and U.S. EPA, Jun 1993.
3. Bass, R.L., Potential Impact of ISTEA Recycled Tire Rubber Provisions in New Mexico, New Mexico State Highway Dept. Central Materials Lab Report, Oct 1992.
4. Heitzman, M.A., State of the Practice - Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier, Publication FHWA-SA-92-022, Federal Highway Administration, Washington D.C., May 1992.
5. Stroup-Gardiner, M., "Cost Factors", Session 6, Workshop Notes, FHWA Crumb Rubber Modifier Workshop, Atlanta, GA., Feb 1993.
6. Chehovits, J.G., "Binder Design Procedures," Session 9, Workshop Notes, FHWA Crumb Rubber Modifier Workshop, Atlanta, GA., Feb 1993.
7. Kandhal, P. and Hanson, D., "Crumb Rubber Modifier (CRM) Technologies," Session 5, Workshop Notes, FHWA Crumb Rubber Modifier Workshop, Atlanta, GA., Feb 1993.
8. Chehovits, J.G. and Hicks R.G., "Mix Design Procedures," Session 10, Workshop Notes, FHWA Crumb Rubber Modifier Workshop, Atlanta, GA., Feb 1993.
9. Takallou, H.B., Evaluation of Mix Ingredients on the Performance of Rubber-Modified Asphalt Mixtures, Ph.D. Dissertation, Oregon State Univ., Corvallis, OR., 1987.
10. Takallou, H.B. and Hicks, R.G., "Development of Improved Mix and Construction Guidelines for Rubber-Modified Asphalt Pavement," Transportation Research Record 1171, Washington D.C., 1988.
11. Heitzman, M.A., "Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier," Transportation Research Record 1339, Washington D.C., 1992.
12. Moulthrop, Cominsky, Kennedy, and Harrigan, "SHRP Asphalt Research - An Overview," Proceedings of the Association of Asphalt Paving Technologists, 1991.

13. Page, G.C., Ruth, B.E., West, R.C., "Florida's Approach Using Ground Tire Rubber in Asphalt Concrete Mixtures", Transportation Research Record 1339, Wash. D.C., 1992.
14. Shook, J.F., Experimental Construction of Rubber-Modified Asphalt Pavements in New York State, New York Department of Transportation Research Report, May 1990.
15. Lawrence, C.E., Killackey, B. J. and Lynch, D.F., Experimental Hot Mix Pavement With Scrap Tire Rubber at Thamesville, Ontario, Ontario Ministry of Transportation, Report #1, Nov 1991.
16. Fager, G.A., "Crumb Rubber Use in Hot Bituminous Pavements (KDOT Experience/1990-1992)," Session 13, Workshop Notes, FHWA Crumb Rubber Modifier Workshop, Denver CO., Mar 1993.
17. Takallou, H.B. and Sainton, A., "Advances in Technology of Asphalt Paving Materials Containing Used Tire Rubber," Transportation Research Record 1339, Washington D.C., 1992.
18. Witczak M.W., State of the Art Synthesis Report, Use of Ground Rubber in Hot Mix Asphalt, Maryland Department of Transportation Report MD-91/01, Jun 1991.
19. Baker Rubber Inc., "Production of Crumb Rubber Modifier (CRM) Material", Session 3, Workshop Notes, FHWA Crumb Rubber Modifier Workshop, Atlanta, GA., Feb 1993.
20. Brown, E.R., "Historical Development," Session 4, Workshop Notes, FHWA Crumb Rubber Modifier Workshop, Atlanta, GA., Feb 1993.
21. The Use of Crumb Rubber in Highway Applications; Catalog and Database, Technology Transfer Center, College of Engineering, Univ. of Nevada-Reno, August, 1994, FAX: (702)-784-1429, Phone: (702)-784-1433.
22. Arrandale, T., "Old Tires, New Solutions," Governing Magazine, May 1992.
23. Letter from FHWA Associate Administrator for Program Development to Regional FHWA Administrators, Subject - Implementation of Section 1038 of the ISTEA of 1991, dated Jun 28, 1993.
24. Green, E.L. and Tolonen, W.J., The Chemical and Physical Properties of Asphalt-Rubber Mixtures--Basic Material Behavior, Report No. ADOT-R5-14(162), Arizona Dept. of Transp., July 1977.
25. Rouse Rubber Industries Inc., Sales Literature on UltraFine Asphalt Cement, "Bulletins 628 and 629 and 633," Vicksburg, MS., Feb 1994.
26. Sainton, A., "A Revolution in Asphalt-Rubber Binders: Flexochape Storable Binder," Proceedings, National Seminar on Asphalt Rubber, ARPG and FHWA, Kansas City, MO., Oct 1989.

27. ECOFLEX Sales Brochure, "Paving the Way to a Better World," Bitumar Research and Development Group, Montreal, Canada.
28. FHWA Report to U.S. Congress as specified in the ISTEA of 1991, A Study of the Use of Recycled Paving Material, Table 2, page 7, Jun 1993.
29. Hansen, K.R. and Stonex, A., Tensile Creep Comparison of Asphalt Cement and Asphalt Rubber Binders, Asphalt Rubber Producers Group Report, Phoenix, Arizona, Oct 1991.
30. Pavlovich, R.D., Shuler, T.S., and Rosner, J.C., Chemical and Physical Properties of Asphalt-Rubber--Phase II, Product Specifications and Test Procedures, Report No. FHWA/AZ-79/121, Arizona DOT, Nov 1979.
31. Brown, E.R. and Foo, K.Y., Evaluation of Variability in Resilient Modulus Test Results, National Center for Asphalt Technology Report No. 91-6, Oct 1989.
32. Schnormeier, R.H. and Jacobson, C.C., "Life Cycle Costs of Asphalt Rubber," Proceedings, National Seminar on Asphalt Rubber, ARPG and FHWA, Kansas City, MO, Oct 1989.
33. Masters, M.F., "Cost Comparisons Between Asphalt-Rubber Systems and Conventional Construction Methods," Proceedings, National Seminar on Asphalt Rubber, ARPG and FHWA, Kansas City, MO, Oct 1989.
34. Roberts, F.L., Kandhal, P.S., Brown, E.R. and Dunning, R.L., Investigation and Evaluation of Ground Tire Rubber in Hot Mix Asphalt, National Center for Asphalt Technology Report No. 89-3, Aug 1989.
35. Roberts, F.L., Kandhal, P.S., Brown, E.R., Lee, D., Kennedy, T.W., Hot Mix Asphalt Materials, Mixture Design and Construction, NAPA Education Foundation, Lanham, MD, 1991.
36. Yoder E.J. and Witczak M.W., Principles of Pavement Design - Chapter 8, 2nd Edition, John Wiley & Sons, Inc, 1975.
37. Bouldin and Collins, "Influence of Binder Rheology on Rut Resistance of Polymer Modified and Unmodified Hot Mix Asphalt," ASTM STP 1108, ASTM Symposium, San Antonio TX, Dec 1990.
38. Cross, S.A. and Brown, E.R., A National Study of Rutting in Hot Mix Asphalt (HMA) Pavements, National Center for Asphalt Technology, Rpt. No. 92-5, Jan 1992.
39. Kandhal, P.S., Cross, S.A. and Brown, E.R., Evaluation of Bituminous Pavements for High Pressure Truck Tires, National Center for Asphalt Technology Rpt. No. 90-2, Dec 1990.
40. Raad, L. and Corcoran J., "Remaining Fatigue Life Analysis: A Comparison Between Conventional Asphalt Concrete and Asphalt-Rubber Hot Mix," Preprint Transportation Research Board, Washington DC, 1993.

41. Kennedy, T.W., Lecture Notes on the subject of SHRP, Professor Training Course in Asphalt Technology, National Center for Asphalt Technology, Auburn AL., Jun 1993.
42. Schnormeier, R.H., "Recycled Tire Rubber in Asphalt," Preprint for Transportation Research Board, 1992.
43. Letter with Interim Design Guide Attached, from California DOT Division of New Technology, to All District Directors, subject - Design Guide for ARHM-GG, dated Feb 28, 1992.
44. Esch, D. C., "Construction and Benefits of Rubber-Modified Asphalt Pavements," Transportation Research Record 860, Washington D.C., 1982.
45. Eaton, R.A., Roberts, R.J., and Blackburn, R.R., Use of Scrap Rubber in Asphalt Pavement Surfaces, Special Rpt 91-27, Cold Regions Research and Engineering Lab, U.S. Army Corps of Engineers, Dec 1991.
46. Stuart, K.D. and Mogawer, W.S., Laboratory Evaluation of Verglimit and PlusRide, FHWA Report No. FHWA-RD-91-013, Mar 1991.
47. Takallou, H.B., McQuillen, J. and Hicks, R.G., Effect of Mix Ingredients on Performance of Rubber-Modified Asphalt Mixtures, FHWA Report No. FHWA-AK-RD-85-05, May 1985.
48. Page, G.C., "Florida Generic Wet Process," Session 13, Workshop Notes, FHWA Crumb Rubber Modifier Workshop, Atlanta, GA., Feb 1993.
49. PlusRide II Asphalt User's Manual, EnvirOtire, Inc., June 1992.
50. Schofield, L., "The History, Development, and Performance of AR at Arizona DOT," Proceedings, National Seminar on Asphalt Rubber, Kansas City, MO., Oct 1989.
51. Ruth, B.E., Evaluation of Ground Tire Rubber in Asphalt Concrete, Final Report, prepared for the Florida DOT, Pub. No. 99700-7520-010, Jan 1992.
52. Van Kirk, J.L., "An Overview of Caltrans Experience with Rubberized Asphalt Concrete," California DOT, Preprint Transportation Research Board, Wash. DC, 1992.
53. Roberts, F.L., Kandhal, P.S., Brown, E.R., Lee, D., Kennedy, T.W., Hot Mix Asphalt Materials, Mixture Design and Construction - Chapter 5, NAPA Education Foundation, Lanham, MD, 1991.
54. Reese, R.E., "Development of a Physical Property Specification for Asphalt-Rubber Binder," Preprint for Proceedings of the Association of Asphalt Technologists, 1994.

55. Cano, J. and Charania, E., "Gap-Graded Asphalt Rubber Hot-Mix Used in the City of Phoenix, AZ," 1992 International Public Works Congress, Boston, MA. Aug 1992.
56. SUPERPAVE Asphalt Mixture Design, National Asphalt Training Center Demonstration Project 101, FHA, Wash. D.C., Feb 1994.
57. Button, Little, Jagadam and Pendleton, "Correlation of Selected Laboratory Compaction Methods with Field Compaction", Proceedings of the Association of Asphalt Technologists, 1993
58. AASHTO Provisional Standards - Jan 1994 Edition, AASHTO Highway Subcommittee on Materials, Washington D.C.
59. Van Kirk, J.L., "CalTrans Experience with Asphalt Rubber Concrete, An Overview and Future Direction," Proceedings, National Seminar on Asphalt Rubber, Kansas City, MO., Oct 1989.
60. Hansen, D.I. and Duncan, G.M., "Characterization of CRM Binders Using SHRP Technology," Preprint Paper # 950707, 74th Transportation Research Board, Washington D.C., Jan 1995.
61. AASHTO Guide for Design of Pavement Structures, Washington D.C., 1986.
62. Gabrielson, J.R., Evaluation of Hot Mix Asphalt Static Creep and Repeated Load Tests, PhD Dissertation, Auburn University, AL, Dec 1992.
63. Anderson, D.A. and Bahia, H.V., "The SHRP Binder Rheological Parameters: Why Are They Required and How Do They Compare to Conventional Properties", Preprint Paper #950793, Transportation Research Board, Washington D.C., 1995.
64. Brown, E.R., Hansen, D.I. and Foo, K.Y., "SHRP Binder Tests: An Initial Experience", NCAT paper for 1994 Transportation Research Board, Jan 1994.
65. Jones, D.R. and Grzybowski, K.F., PRI Asphalt Technologies Inc, Tampa, FL, "Practical Aspects of Performing the SHRP Binder Tests," Notes presented at the Southeast Region User-Producer Meeting at Auburn University, Sept 1993.
66. Steel, R.G. and Torrie, J.H., "Principles and Procedures of Statistics, A Biometrical Approach", 2nd Edition, McGraw-Hill Publishing Co., 1980.

APPENDIX A

Material Properties and Preparation of AR

This appendix includes a chemical analysis of the CRM (provided by Rouse Rubber Industries Inc.), and asphalt grading summary sheets for the AC-10 and AC-30 (provided by Lion Oil Co). Also included are the procedures used to prepare the reacted blends of Phase I and the AR used for the wet mixes of Phase II, as well as the procedures followed for taking the Brookfield viscosity measurements during the reaction monitoring. Figure A.1 shows the viscosity measurements plotted versus time during the reaction period for the four reacted blends of phase I and one AR of phase II.

CRM CHEMICAL ANALYSIS

Acetone extract 23% max
(ASTM D297)

Ash 7% max
(ASTM D297B)

Carbon Black 34% max
(ASTM D297B)

Rubber hydrocarbon 42% min
(By difference)

Specific gravity 1.15±.02
(ASTM D297)

Moisture 1% max

Specific Surface
Area (m²/gram) -

Bulk Density 26 - 28
(lbs./ft²)

AC-10

ASPHALT GRADING SUMMARY SHEET - SHRP SPECIFICATION VERSION (FINAL)

AC95107-053

ABS.VIS.928P 77°F PEN 124 DMM

Asphalt ID: Lion Oil AC-10 Operator ID: JAS

State: SHRP

Date: 04-21-95

| | | | | | | | | |
|-----------------------------------|--------------------------|-----------------------------------|-----------------------------------|--------------------------|-------------------------------|--------------------------|------------------|--------------------|
| Original | | RTFOT | RTFOT + PAV residue | | | | | |
| Flash Pt: °C | | Loss% | Time/Temp after PAV: | | | | | |
| 125°C: 458 cP | | | Physical Hardening Index | | | | | |
| Viscosity @ 135°C: 280 cP | | | | | | | | |
| 145°C: 181 cP | | | | | | | | |
| Dynamic Shear 10 rad/s (1.5Hz) | | Dynamic Shear 10 rad/s (1.5Hz) | Dynamic Shear 10 rad/s (1.5Hz) | | Flexural Creep (at 60 sec) | | | DT 1mm/min |
| Temp. (°C) | G*/sin d (kPa) >1 kPa | G*/sin d (kPa) >2.2 kPa | Temp. °C | G* sin d (MPa) <5 MPa | Temp. °C | Stiffness, S <300 MPa | Slope, m >0.3 | F. Strain >1.0% |
| 34 | | | 40 | | 12 | | | |
| 40 | | | 37 | | 6 | | | |
| 46 | | | 34 | | 0 | | | |
| 52 | 3.352 | 5.346 | 31 | | -6 | | | |
| 58 | 1.623 | 2.474 | 28 | 0.329 | -12 | 115.7 | 0.395 | |
| 64 | | | 25 | | -18 | 243.0 | 0.339 | |
| 70 | | | 22 | 0.635 | -24 | | | |
| 76 | | | 19 | 0.888 | -30 | | | |
| 82 | | | 16 | 1.314 | -36 | | | |
| 88 | | | 13 | | -42 | | | |
| 94 | | | 10 | | -48 | | | |
| 100 | | | 7 | | -54 | | | |

Grade: PG58 - 28

AC-30

| |
|--|
| ASPHALT GRADING SUMMARY SHEET - SHRP SPECIFICATION VERSION (FINAL) |
|--|

AC95107-052

ABS.VIS.2731P 77°F PEN 57 DMM

Asphalt ID: Lion Oil AC-30 Operator ID: JAS

State: SHRP

Date: 04-21-95

| Original | | RTFOT | RTFOT + PAV residue | | | | | |
|-----------------------------------|--------------------------|-----------------------------------|-----------------------------------|--------------------------|-------------------------------|--------------------------|------------------|--------------------|
| Flash Pt: °C | | Loss% | Time/Temp after PAV: | | | | | |
| 125°C: 814 cP | | | Physical Hardening Index | | | | | |
| Viscosity @ 135°C: 474 cP | | | | | | | | |
| 145°C: 289 cP | | | | | | | | |
| Dynamic Shear 10 rad/s (1.5Hz) | | Dynamic Shear 10 rad/s (1.5Hz) | Dynamic Shear 10 rad/s (1.5Hz) | | Flexural Creep (at 60 sec) | | | DT 1mm/min |
| Temp. (°C) | G*/sin d (kPa) >1 kPa | G*/sin d (kPa) >2.2 kPa | Temp. °C | G* sin d (MPa) <5 MPa | Temp. °C | Stiffness, S <300 MPa | Slope, m >0.3 | F. Strain >1.0% |
| 34 | | | 40 | | 12 | | | |
| 40 | | | 37 | | 6 | | | |
| 46 | | | 34 | | 0 | | | |
| 52 | 8.292 | | 31 | | -6 | 131.3 | 0.381 | |
| 58 | 3.877 | 6.744 | 28 | 0.804 | -12 | 242.9 | 0.303 | |
| 64 | 1.900 | 3.439 | 25 | 1.146 | -18 | | | |
| 70 | | 2.181 | 22 | 1.759 | -24 | | | |
| 76 | | | 19 | | -30 | | | |
| 82 | | | 16 | | -36 | | | |
| 88 | | | 13 | | -42 | | | |
| 94 | | | 10 | | -48 | | | |
| 100 | | | 7 | | -54 | | | |

Grade: PG64 - 22

NCAT PROCEDURE FOR PREPARING CRUMB RUBBER MODIFIED ASPHALT USING THE WET METHOD

- A known weight of asphalt is heated to 350° F or to the desired reaction temperature.
- After the desired temperature is reached, the proper percentage of crumb rubber, by weight of asphalt, is added to the asphalt in approximately 1 cup increments. The material is thoroughly mixed after each addition using a high shear mixer. The NCAT lab uses an electric drill with a paint mixing attachment. The initial mixing process is achieved within 5-10 minutes.
- The material is mixed using the high shear device every 15 minutes for the first hour and then once an hour should be sufficient. Mixing is also performed before a viscosity measurement is taken.
- In order to monitor the modification of the asphalt, the Brookfield Viscometer is used to measure the viscosity of the material at various times of reaction.
- The modification of the asphalt binder is completed when the viscosity begins to decrease from its highest value.

PROCEDURE FOR BROOKFIELD VISCOMETER MEASUREMENTS

- Spindle #3 and 20 RPM's are used to make the viscosity measurement. The apparatus is submerged in the liquid to the proper depth for 1 minute to achieve temperature equilibrium before the measurements are begun.
- The motor is then engaged for 1 minute before the first viscosity is read. The next two viscosity readings should follow an additional minute of rotation. To summarize, three viscosity readings are taken over a 3 minute period of time after the motor has been engaged.
- The three viscosity measurements are averaged to indicate a viscosity value for the material at the median time of reaction.

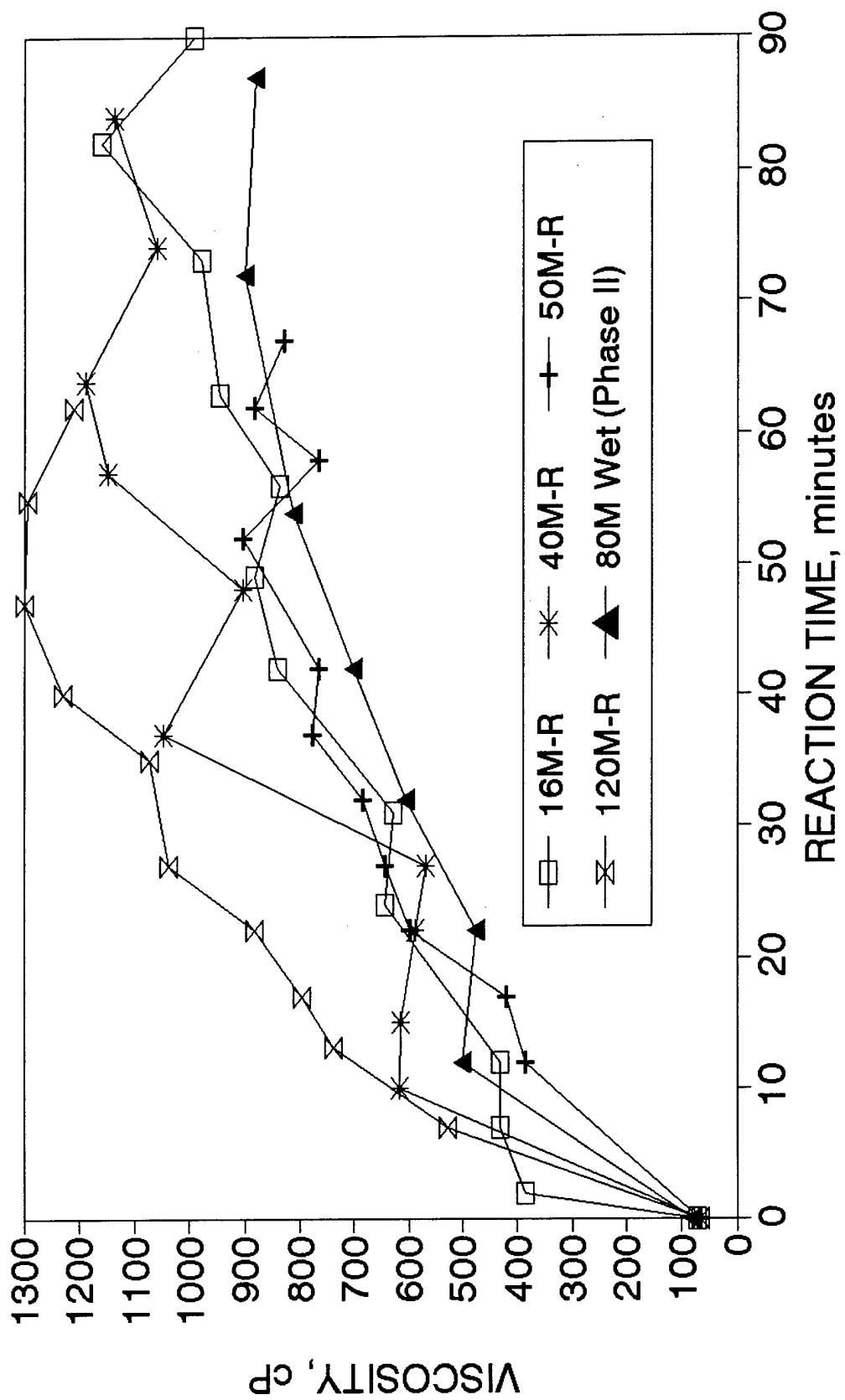


Figure A.1 Reaction Monitoring with Brookfield Viscometer

APPENDIX B

Individual DSR Test Results

The results of all the individual DSR tests are in Tables B.1 through B.4. These tables give G^* , δ , and the respective SUPERPAVE parameter for both sample repetitions, as well as an average and coefficient of variation (CV). The CV was used rather than the standard deviation because the standard deviation of G^* increased proportional to G^* 's magnitude, which increased by more than a factor of 10 over the 18 °C range. The CV remained relatively constant, thus an average CV was reported. Table B.1 is for the 10 *primary* blends with no aging, Table B.2 for the same 10 blends with TFO aging and Table B.3 for the same 10 blends with PAV aging. Table B.4 is for the five *supplemental* blends with PAV aging.

Table B.1 DSR Results on Original (No Aging) Blends

| Blend | @ 58C | | | | @ 64C | | | | @ 70C | | | | @ 76C | | | |
|-------|--------|----------|---------------|----------|----------|-------|---------------|----------|--------|----------|---------------|-------|----------|-------|---------------|-------|
| | G*, Pa | delta | G*/sin(delta) | delta | G*, Pa | delta | G*/sin(delta) | delta | G*, Pa | delta | G*/sin(delta) | delta | G*, Pa | delta | G*/sin(delta) | delta |
| AC-10 | REP#1 | 1.41E+03 | 88.56 | 1.41E+03 | 6.50E+02 | 89.33 | 6.50E+02 | 3.20E+02 | 89.98 | 3.20E+02 | 3.20E+02 | 89.98 | 1.69E+02 | 89.47 | 1.69E+02 | 89.47 |
| | REP#2 | 1.39E+03 | 88.47 | 1.39E+03 | 6.60E+02 | 89.09 | 6.60E+02 | 3.35E+02 | 89.56 | 3.35E+02 | 3.35E+02 | 89.56 | 1.74E+02 | 89.95 | 1.74E+02 | 89.95 |
| | AVG | 1.40E+03 | 88.52 | 1.40E+03 | 6.55E+02 | 89.21 | 6.55E+02 | 3.28E+02 | 89.77 | 3.28E+02 | 3.28E+02 | 89.77 | 1.72E+02 | 89.71 | 1.72E+02 | 89.71 |
| | CV | 1.01% | 0.07% | 1.01% | 1.08% | 0.19% | 1.08% | 3.24% | 0.33% | 3.24% | 3.24% | 0.33% | 2.06% | 0.38% | 2.06% | 0.38% |
| AC-30 | REP#1 | 2.77E+03 | 87.94 | 2.77E+03 | 1.21E+03 | 88.91 | 1.21E+03 | 5.79E+02 | 89.18 | 5.79E+02 | 5.79E+02 | 89.18 | 2.90E+02 | 89.69 | 2.90E+02 | 89.69 |
| | REP#2 | 2.65E+03 | 87.76 | 2.65E+03 | 1.13E+03 | 88.79 | 1.13E+03 | 5.43E+02 | 89.32 | 5.43E+02 | 5.43E+02 | 89.32 | 2.74E+02 | 89.70 | 2.74E+02 | 89.70 |
| | AVG | 2.71E+03 | 87.85 | 2.71E+03 | 1.17E+03 | 88.85 | 1.17E+03 | 5.61E+02 | 89.25 | 5.61E+02 | 5.61E+02 | 89.25 | 2.82E+02 | 89.70 | 2.82E+02 | 89.70 |
| | CV | 3.13% | 0.14% | 3.12% | 4.83% | 0.10% | 4.83% | 4.54% | 0.11% | 4.54% | 4.54% | 0.11% | 4.01% | 0.01% | 4.01% | 0.01% |
| 16M-R | REP#1 | 5.61E+03 | 72.06 | 5.90E+03 | 3.01E+03 | 75.52 | 3.11E+03 | 1.66E+03 | 78.75 | 1.69E+03 | 1.69E+03 | 78.75 | 9.35E+02 | 81.35 | 9.46E+02 | 81.35 |
| | REP#2 | 5.44E+03 | 71.50 | 5.74E+03 | 2.97E+03 | 74.96 | 3.08E+03 | 1.66E+03 | 78.01 | 1.70E+03 | 1.70E+03 | 78.01 | 9.39E+02 | 80.92 | 9.51E+02 | 80.92 |
| | AVG | 5.53E+03 | 71.78 | 5.82E+03 | 2.99E+03 | 75.24 | 3.09E+03 | 1.66E+03 | 78.38 | 1.69E+03 | 1.69E+03 | 78.38 | 9.37E+02 | 81.14 | 9.48E+02 | 81.14 |
| | CV | 2.18% | 0.55% | 1.95% | 0.95% | 0.53% | 0.76% | 0.00% | 0.67% | 0.19% | 0.19% | 0.67% | 0.30% | 0.37% | 0.38% | 0.37% |
| 16M-U | REP#1 | 2.74E+03 | 85.33 | 2.75E+03 | 1.37E+03 | 86.51 | 1.37E+03 | 7.28E+02 | 87.03 | 7.29E+02 | 7.29E+02 | 87.03 | 3.90E+02 | 87.50 | 3.90E+02 | 87.50 |
| | REP#2 | 2.70E+03 | 85.58 | 2.71E+03 | 1.35E+03 | 86.59 | 1.35E+03 | 7.25E+02 | 87.09 | 7.26E+02 | 7.26E+02 | 87.09 | 3.94E+02 | 87.55 | 3.94E+02 | 87.55 |
| | AVG | 2.72E+03 | 85.46 | 2.73E+03 | 1.36E+03 | 86.55 | 1.36E+03 | 7.27E+02 | 87.06 | 7.27E+02 | 7.27E+02 | 87.06 | 3.92E+02 | 87.53 | 3.92E+02 | 87.53 |
| | CV | 1.04% | 0.21% | 1.06% | 1.04% | 0.07% | 1.05% | 0.29% | 0.05% | 0.30% | 0.30% | 0.05% | 0.72% | 0.04% | 0.72% | 0.04% |
| 40M-R | REP#1 | 4.96E+03 | 76.22 | 5.11E+03 | 2.64E+03 | 79.60 | 2.68E+03 | 1.47E+03 | 81.96 | 1.48E+03 | 1.48E+03 | 81.96 | 7.05E+02 | 84.77 | 7.08E+02 | 84.77 |
| | REP#2 | 4.92E+03 | 76.67 | 5.06E+03 | 2.45E+03 | 80.09 | 2.49E+03 | 1.28E+03 | 82.57 | 1.29E+03 | 1.29E+03 | 82.57 | 6.97E+02 | 84.33 | 7.00E+02 | 84.33 |
| | AVG | 4.94E+03 | 76.45 | 5.08E+03 | 2.55E+03 | 79.85 | 2.59E+03 | 1.38E+03 | 82.27 | 1.39E+03 | 1.39E+03 | 82.27 | 7.01E+02 | 84.55 | 7.04E+02 | 84.55 |
| | CV | 0.57% | 0.42% | 0.71% | 5.28% | 0.43% | 5.39% | 9.77% | 0.52% | 9.87% | 9.87% | 0.52% | 0.81% | 0.37% | 0.76% | 0.37% |
| 40M-U | REP#1 | 3.55E+03 | 85.02 | 3.56E+03 | 1.74E+03 | 86.40 | 1.74E+03 | 9.21E+02 | 87.39 | 9.22E+02 | 9.22E+02 | 87.39 | 5.47E+02 | 87.74 | 5.47E+02 | 87.74 |
| | REP#2 | 3.30E+03 | 85.89 | 3.31E+03 | 1.71E+03 | 86.97 | 1.71E+03 | 9.32E+02 | 87.89 | 9.33E+02 | 9.33E+02 | 87.89 | 5.20E+02 | 88.68 | 5.20E+02 | 88.68 |
| | AVG | 3.43E+03 | 85.46 | 3.44E+03 | 1.73E+03 | 86.69 | 1.73E+03 | 9.27E+02 | 87.64 | 9.27E+02 | 9.27E+02 | 87.64 | 5.34E+02 | 88.21 | 5.34E+02 | 88.21 |
| | CV | 5.16% | 0.72% | 5.25% | 1.23% | 0.46% | 1.27% | 0.84% | 0.40% | 0.81% | 0.81% | 0.40% | 3.58% | 0.75% | 3.61% | 0.75% |

Continued on Next Page

Page 1 of 2

Table B.1 DSR Results on Original (No Aging) Blends

| Blend | @ 58C | | | | @ 64C | | | | @ 70C | | | | @ 76C | | | |
|-----------------------------------|----------|----------|----------|--------|----------|----------|----------|--------|----------|----------|----------|--------|----------|----------|----------|--------|
| | REP #1 | REP #2 | AVG | CV | REP #1 | REP #2 | AVG | CV | REP #1 | REP #2 | AVG | CV | REP #1 | REP #2 | AVG | CV |
| 50M-R | 5.28E+03 | 5.25E+03 | 5.27E+03 | 0.40% | 5.46E+03 | 5.42E+03 | 5.44E+03 | 0.40% | 5.71E+03 | 5.68E+03 | 5.69E+03 | 0.40% | 5.96E+03 | 5.93E+03 | 5.94E+03 | 0.40% |
| | 75.41 | 75.41 | 75.41 | 0.00% | 83.85 | 83.85 | 83.85 | 0.00% | 91.97 | 91.97 | 91.97 | 0.00% | 99.99 | 99.99 | 99.99 | 0.00% |
| | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta |
| | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa |
| 50M-U | 4.04E+03 | 3.78E+03 | 3.91E+03 | 4.70% | 4.06E+03 | 3.80E+03 | 3.93E+03 | 4.72% | 4.12E+03 | 3.86E+03 | 3.99E+03 | 4.74% | 4.28E+03 | 4.02E+03 | 4.15E+03 | 4.76% |
| | 83.85 | 84.02 | 83.94 | 0.14% | 83.85 | 84.02 | 83.94 | 0.14% | 83.85 | 84.02 | 83.94 | 0.14% | 83.85 | 84.02 | 83.94 | 0.14% |
| | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta |
| | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa |
| 120M-R | 4.76E+03 | 4.98E+03 | 4.87E+03 | 3.19% | 4.91E+03 | 5.14E+03 | 5.02E+03 | 3.32% | 5.07E+03 | 5.30E+03 | 5.18E+03 | 3.40% | 5.35E+03 | 5.58E+03 | 5.46E+03 | 3.52% |
| | 75.94 | 75.54 | 75.74 | 0.37% | 75.94 | 75.54 | 75.74 | 0.37% | 75.94 | 75.54 | 75.74 | 0.37% | 75.94 | 75.54 | 75.74 | 0.37% |
| | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta |
| | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa |
| 120M-U | 3.21E+03 | 3.40E+03 | 3.31E+03 | 4.07% | 3.22E+03 | 3.41E+03 | 3.31E+03 | 4.09% | 3.27E+03 | 3.46E+03 | 3.36E+03 | 4.10% | 3.32E+03 | 3.51E+03 | 3.41E+03 | 4.11% |
| | 85.76 | 85.52 | 85.64 | 0.20% | 85.76 | 85.52 | 85.64 | 0.20% | 85.76 | 85.52 | 85.64 | 0.20% | 85.76 | 85.52 | 85.64 | 0.20% |
| | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta | delta |
| | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa | G*, Pa |
| Continued from Previous Page | | | | | | | | | | | | | | | | |
| Avg. CV for G* = 2.56% | | | | | | | | | | | | | | | | |
| Avg. CV for delta = 0.25% | | | | | | | | | | | | | | | | |
| Avg. CV for G*/sin(delta) = 2.57% | | | | | | | | | | | | | | | | |

Table B.2 DSR Results on Short-Term Aged (TFO) Blends

| Blend | @ 58C | | | | @ 64C | | | | @ 70C | | | | @ 76C | | | |
|-------|--------|----------|---------------|----------|----------|-------|---------------|--|----------|-------|---------------|--|----------|-------|---------------|--|
| | G*, Pa | delta | G*/sin(delta) | | G*, Pa | delta | G*/sin(delta) | | G*, Pa | delta | G*/sin(delta) | | G*, Pa | delta | G*/sin(delta) | |
| AC-10 | REP#1 | 2.33E+03 | 86.94 | 2.33E+03 | 1.09E+03 | 88.18 | 1.09E+03 | | 5.36E+02 | 89.09 | 5.36E+02 | | 2.74E+02 | 89.91 | 2.74E+02 | |
| | REP#2 | 2.24E+03 | 86.78 | 2.24E+03 | 1.03E+03 | 88.00 | 1.03E+03 | | 5.04E+02 | 88.79 | 5.04E+02 | | 2.57E+02 | 89.38 | 2.57E+02 | |
| | AVG | 2.29E+03 | 86.86 | 2.29E+03 | 1.06E+03 | 88.09 | 1.06E+03 | | 5.20E+02 | 88.94 | 5.20E+02 | | 2.66E+02 | 89.65 | 2.66E+02 | |
| | CV | 2.79% | 0.13% | 2.77% | 4.00% | 0.14% | 4.00% | | 4.35% | 0.24% | 4.34% | | 4.53% | 0.42% | 4.52% | |
| AC-30 | REP#1 | 5.17E+03 | 86.01 | 5.18E+03 | 2.27E+03 | 87.41 | 2.27E+03 | | 1.00E+03 | 88.47 | 1.00E+03 | | 4.78E+02 | 89.01 | 4.78E+02 | |
| | REP#2 | 5.14E+03 | 85.95 | 5.15E+03 | 2.29E+03 | 87.28 | 2.29E+03 | | 1.02E+03 | 88.56 | 1.02E+03 | | 4.92E+02 | 89.13 | 4.92E+02 | |
| | AVG | 5.16E+03 | 85.98 | 5.17E+03 | 2.28E+03 | 87.35 | 2.28E+03 | | 1.01E+03 | 88.52 | 1.01E+03 | | 4.85E+02 | 89.07 | 4.85E+02 | |
| | CV | 0.41% | 0.05% | 0.41% | 0.62% | 0.11% | 0.63% | | 1.40% | 0.07% | 1.40% | | 2.04% | 0.10% | 2.04% | |
| 16M-R | REP#1 | 7.47E+03 | 70.33 | 7.93E+03 | 3.99E+03 | 73.50 | 4.16E+03 | | 2.14E+03 | 76.28 | 2.20E+03 | | 1.20E+03 | 78.61 | 1.22E+03 | |
| | REP#2 | 7.45E+03 | 69.86 | 7.94E+03 | 4.02E+03 | 72.92 | 4.21E+03 | | 2.24E+03 | 75.46 | 2.31E+03 | | 1.26E+03 | 77.82 | 1.29E+03 | |
| | AVG | 7.46E+03 | 70.10 | 7.93E+03 | 4.01E+03 | 73.21 | 4.18E+03 | | 2.19E+03 | 75.87 | 2.26E+03 | | 1.23E+03 | 78.22 | 1.26E+03 | |
| | CV | 0.19% | 0.47% | 0.02% | 0.53% | 0.56% | 0.75% | | 3.23% | 0.76% | 3.48% | | 3.45% | 0.71% | 3.65% | |
| 16M-U | REP#1 | 5.74E+03 | 81.95 | 5.80E+03 | 2.72E+03 | 83.90 | 2.74E+03 | | 1.37E+03 | 85.16 | 1.37E+03 | | 7.31E+02 | 85.85 | 7.33E+02 | |
| | REP#2 | 5.58E+03 | 82.05 | 5.63E+03 | 2.67E+03 | 84.00 | 2.68E+03 | | 1.39E+03 | 84.91 | 1.40E+03 | | 7.38E+02 | 85.41 | 7.40E+02 | |
| | AVG | 5.66E+03 | 82.00 | 5.72E+03 | 2.70E+03 | 83.95 | 2.71E+03 | | 1.38E+03 | 85.04 | 1.39E+03 | | 7.35E+02 | 85.63 | 7.37E+02 | |
| | CV | 2.00% | 0.09% | 2.02% | 1.31% | 0.08% | 1.32% | | 1.02% | 0.21% | 1.05% | | 0.67% | 0.36% | 0.72% | |
| 40M-R | REP#1 | 6.16E+03 | 73.40 | 6.43E+03 | 3.13E+03 | 76.29 | 3.22E+03 | | 1.68E+03 | 78.80 | 1.71E+03 | | 9.18E+02 | 80.70 | 9.30E+02 | |
| | REP#2 | 6.63E+03 | 73.91 | 6.90E+03 | 3.40E+03 | 76.99 | 3.49E+03 | | 1.86E+03 | 79.43 | 1.89E+03 | | 1.04E+03 | 81.31 | 1.05E+03 | |
| | AVG | 6.40E+03 | 73.66 | 6.66E+03 | 3.27E+03 | 76.64 | 3.36E+03 | | 1.77E+03 | 79.12 | 1.80E+03 | | 9.79E+02 | 81.01 | 9.91E+02 | |
| | CV | 5.20% | 0.49% | 5.01% | 5.85% | 0.65% | 5.64% | | 7.19% | 0.56% | 7.04% | | 8.81% | 0.53% | 8.69% | |
| 40M-U | REP#1 | 5.49E+03 | 83.43 | 5.53E+03 | 2.57E+03 | 85.53 | 2.58E+03 | | 1.30E+03 | 86.73 | 1.30E+03 | | 6.91E+02 | 87.60 | 6.92E+02 | |
| | REP#2 | 5.19E+03 | 83.83 | 5.22E+03 | 2.50E+03 | 85.20 | 2.51E+03 | | 1.27E+03 | 86.35 | 1.27E+03 | | 6.90E+02 | 87.12 | 6.91E+02 | |
| | AVG | 5.34E+03 | 83.63 | 5.37E+03 | 2.54E+03 | 85.37 | 2.54E+03 | | 1.29E+03 | 86.54 | 1.29E+03 | | 6.91E+02 | 87.36 | 6.91E+02 | |
| | CV | 3.97% | 0.34% | 4.03% | 1.95% | 0.27% | 1.92% | | 1.65% | 0.31% | 1.62% | | 0.10% | 0.39% | 0.08% | |

Continued on Next Page

Page 1 of 2

Table B.2 DSR Results on Short-Term Aged (TFO) Blends

| Blend | @ 58C | | | | @ 64C | | | | @ 70C | | | | @ 76C | | | |
|-----------------------------------|-------|----------|-------|----------|----------|-------|---------------|----------|-------|---------------|----------|-------|---------------|--------|-------|---------------|
| | REP#1 | REP#2 | AVG | CV | G*, Pa | delta | G*/sin(delta) | G*, Pa | delta | G*/sin(delta) | G*, Pa | delta | G*/sin(delta) | G*, Pa | delta | G*/sin(delta) |
| 50M-R | REP#1 | 6.55E+03 | 73.09 | 6.85E+03 | 3.43E+03 | 76.39 | 3.53E+03 | 1.85E+03 | 79.13 | 1.88E+03 | 1.03E+03 | 81.34 | 1.04E+03 | | | |
| | REP#2 | 6.37E+03 | 73.38 | 6.65E+03 | 3.34E+03 | 76.71 | 3.43E+03 | 1.76E+03 | 79.25 | 1.79E+03 | 9.65E+02 | 81.43 | 9.76E+02 | | | |
| | AVG | 6.46E+03 | 73.24 | 6.75E+03 | 3.39E+03 | 76.55 | 3.48E+03 | 1.81E+03 | 79.19 | 1.84E+03 | 9.98E+02 | 81.39 | 1.01E+03 | | | |
| | CV | 1.97% | 0.28% | 2.08% | 1.88% | 0.30% | 1.97% | 3.53% | 0.11% | 3.55% | 4.61% | 0.08% | 4.62% | | | |
| 50M-U | REP#1 | 4.95E+03 | 83.41 | 4.98E+03 | 2.39E+03 | 85.34 | 2.40E+03 | 1.30E+03 | 86.41 | 1.30E+03 | 7.20E+02 | 87.19 | 7.21E+02 | | | |
| | REP#2 | 5.09E+03 | 83.40 | 5.12E+03 | 2.48E+03 | 85.02 | 2.49E+03 | 1.31E+03 | 86.10 | 1.31E+03 | 7.30E+02 | 86.88 | 7.31E+02 | | | |
| | AVG | 5.02E+03 | 83.41 | 5.05E+03 | 2.44E+03 | 85.18 | 2.44E+03 | 1.31E+03 | 86.26 | 1.31E+03 | 7.25E+02 | 87.04 | 7.26E+02 | | | |
| | CV | 1.97% | 0.01% | 1.97% | 2.61% | 0.27% | 2.65% | 0.54% | 0.25% | 0.57% | 0.98% | 0.25% | 1.00% | | | |
| 120M-R | REP#1 | 6.46E+03 | 70.17 | 6.87E+03 | 3.60E+03 | 73.05 | 3.76E+03 | 1.97E+03 | 76.29 | 2.03E+03 | 1.12E+03 | 78.99 | 1.14E+03 | | | |
| | REP#2 | 7.00E+03 | 69.83 | 7.46E+03 | 3.77E+03 | 72.85 | 3.95E+03 | 2.06E+03 | 76.07 | 2.12E+03 | 1.16E+03 | 79.01 | 1.18E+03 | | | |
| | AVG | 6.73E+03 | 70.00 | 7.16E+03 | 3.69E+03 | 72.95 | 3.85E+03 | 2.02E+03 | 76.18 | 2.08E+03 | 1.14E+03 | 79.00 | 1.16E+03 | | | |
| | CV | 5.67% | 0.34% | 5.83% | 3.26% | 0.19% | 3.34% | 3.16% | 0.20% | 3.23% | 2.48% | 0.02% | 2.48% | | | |
| 120M-U | REP#1 | 7.40E+03 | 80.53 | 7.50E+03 | 3.47E+03 | 83.21 | 3.49E+03 | 1.72E+03 | 85.29 | 1.73E+03 | 9.04E+02 | 86.48 | 9.06E+02 | | | |
| | REP#2 | 7.23E+03 | 80.63 | 7.33E+03 | 3.40E+03 | 83.36 | 3.42E+03 | 1.69E+03 | 85.06 | 1.70E+03 | 8.83E+02 | 86.31 | 8.85E+02 | | | |
| | AVG | 7.32E+03 | 80.58 | 7.41E+03 | 3.44E+03 | 83.29 | 3.46E+03 | 1.71E+03 | 85.18 | 1.71E+03 | 8.94E+02 | 86.40 | 8.95E+02 | | | |
| | CV | 1.64% | 0.09% | 1.66% | 1.44% | 0.13% | 1.46% | 1.24% | 0.19% | 1.22% | 1.66% | 0.14% | 1.65% | | | |
| Continued from Previous Page | | | | | | | | | | | | | | | | |
| Avg. CV for G* = 2.64% | | | | | | | | | | | | | | | | |
| Avg. CV for delta = 0.27% | | | | | | | | | | | | | | | | |
| Avg. CV for G*/sin(delta) = 2.66% | | | | | | | | | | | | | | | | |

Table B.3 DSR Results on Long-Term Aged (PAV) Blends

| Blend | @ 10C | | | | @ 16C | | | | @ 22C | | | | @ 28C | | | |
|-------|--------|----------|------------------------|----------|----------|-------|------------------------|----------|--------|----------|------------------------|-------|----------|----------|------------------------|--------|
| | G*, Pa | delta | G* \times sin(delta) | delta | G*, Pa | delta | G* \times sin(delta) | delta | G*, Pa | delta | G* \times sin(delta) | delta | G*, Pa | delta | G* \times sin(delta) | delta |
| AC-10 | REP#1 | 1.92E+07 | 38.83 | 1.20E+07 | 8.27E+06 | 47.29 | 6.08E+06 | 3.17E+06 | 54.89 | 2.59E+06 | 1.13E+06 | 61.03 | 9.89E+05 | 61.03 | 9.89E+05 | 61.03 |
| | REP#2 | 2.02E+07 | 39.14 | 1.28E+07 | 9.13E+06 | 46.32 | 6.60E+06 | 3.52E+06 | 54.30 | 2.86E+06 | 1.21E+06 | 61.22 | 1.06E+06 | 1.21E+06 | 1.06E+06 | 61.22 |
| | AVG | 1.97E+07 | 38.99 | 1.24E+07 | 8.70E+06 | 46.81 | 6.34E+06 | 3.35E+06 | 54.60 | 2.73E+06 | 1.17E+06 | 61.13 | 1.02E+06 | 1.17E+06 | 1.02E+06 | 61.13 |
| | CV | 3.59% | 0.56% | 4.06% | 6.99% | 1.47% | 5.87% | 7.40% | 0.76% | 6.88% | 4.83% | 0.22% | 4.96% | 4.83% | 0.22% | 4.96% |
| AC-30 | REP#1 | 4.30E+07 | 30.81 | 2.20E+07 | 2.06E+07 | 39.28 | 1.30E+07 | 8.67E+06 | 48.21 | 6.46E+06 | 3.24E+06 | 56.09 | 2.69E+06 | 3.24E+06 | 2.69E+06 | 56.09 |
| | REP#2 | 4.02E+07 | 31.36 | 2.09E+07 | 2.00E+07 | 38.67 | 1.25E+07 | 8.40E+06 | 46.60 | 6.10E+06 | 3.17E+06 | 54.64 | 2.59E+06 | 3.17E+06 | 2.59E+06 | 54.64 |
| | AVG | 4.16E+07 | 31.09 | 2.15E+07 | 2.03E+07 | 38.98 | 1.28E+07 | 8.54E+06 | 47.41 | 6.28E+06 | 3.21E+06 | 55.37 | 2.64E+06 | 3.21E+06 | 2.64E+06 | 55.37 |
| | CV | 4.76% | 1.25% | 3.63% | 2.09% | 1.11% | 3.02% | 2.24% | 2.40% | 4.06% | 1.54% | 1.85% | 2.78% | 1.54% | 1.85% | 2.78% |
| 16M-R | REP#1 | 8.37E+06 | 41.11 | 5.50E+06 | 3.76E+06 | 46.88 | 2.74E+06 | 1.57E+06 | 51.89 | 1.23E+06 | 6.49E+05 | 55.33 | 5.34E+05 | 6.49E+05 | 5.34E+05 | 55.33 |
| | REP#2 | 7.61E+06 | 42.78 | 5.17E+06 | 3.70E+06 | 48.00 | 2.75E+06 | 1.58E+06 | 52.71 | 1.25E+06 | 7.03E+05 | 56.25 | 5.85E+05 | 7.03E+05 | 5.85E+05 | 56.25 |
| | AVG | 7.99E+06 | 41.95 | 5.34E+06 | 3.73E+06 | 47.44 | 2.75E+06 | 1.57E+06 | 52.20 | 1.24E+06 | 6.76E+05 | 55.79 | 5.59E+05 | 6.76E+05 | 5.59E+05 | 55.79 |
| | CV | 6.71% | 2.82% | 4.41% | 1.15% | 1.67% | 0.12% | 0.27% | 1.38% | 1.25% | 5.71% | 1.17% | 6.48% | 5.71% | 1.17% | 6.48% |
| 16M-U | REP#1 | 8.85E+06 | 39.82 | 5.67E+06 | 4.58E+06 | 45.52 | 3.27E+06 | 2.02E+06 | 50.96 | 1.57E+06 | 8.37E+05 | 55.78 | 6.92E+05 | 8.37E+05 | 6.92E+05 | 55.78 |
| | REP#2 | 1.04E+07 | 40.13 | 6.68E+06 | 5.06E+06 | 45.96 | 3.64E+06 | 2.29E+06 | 51.04 | 1.78E+06 | 1.02E+06 | 55.39 | 8.36E+05 | 1.02E+06 | 8.36E+05 | 55.39 |
| | AVG | 9.61E+06 | 39.98 | 6.18E+06 | 4.82E+06 | 45.74 | 3.45E+06 | 2.15E+06 | 51.00 | 1.67E+06 | 9.26E+05 | 55.59 | 7.64E+05 | 9.26E+05 | 7.64E+05 | 55.59 |
| | CV | 11.15% | 0.55% | 11.61% | 7.12% | 0.68% | 7.64% | 8.86% | 0.11% | 8.94% | 13.66% | 0.50% | 13.33% | 13.66% | 0.50% | 13.33% |
| 40M-R | REP#1 | 8.55E+06 | 42.14 | 5.74E+06 | 3.76E+06 | 47.72 | 2.78E+06 | 1.57E+06 | 52.30 | 1.24E+06 | 6.46E+05 | 55.60 | 5.33E+05 | 6.46E+05 | 5.33E+05 | 55.60 |
| | REP#2 | 7.52E+06 | 42.49 | 5.08E+06 | 3.64E+06 | 47.72 | 2.69E+06 | 1.62E+06 | 52.06 | 1.28E+06 | 6.97E+05 | 55.45 | 5.74E+05 | 6.97E+05 | 5.74E+05 | 55.45 |
| | AVG | 8.04E+06 | 42.32 | 5.41E+06 | 3.70E+06 | 47.72 | 2.74E+06 | 1.59E+06 | 52.18 | 1.26E+06 | 6.72E+05 | 55.53 | 5.54E+05 | 6.72E+05 | 5.54E+05 | 55.53 |
| | CV | 9.07% | 0.58% | 8.60% | 2.32% | 0.00% | 2.32% | 2.15% | 0.33% | 1.92% | 5.43% | 0.19% | 5.30% | 5.43% | 0.19% | 5.30% |
| 40M-U | REP#1 | 1.22E+07 | 37.58 | 7.42E+06 | 5.79E+06 | 43.35 | 3.98E+06 | 2.69E+06 | 47.85 | 2.00E+06 | 1.19E+06 | 51.45 | 9.27E+05 | 1.19E+06 | 9.27E+05 | 51.45 |
| | REP#2 | 1.13E+07 | 38.38 | 7.04E+06 | 5.79E+06 | 43.78 | 4.01E+06 | 2.81E+06 | 48.00 | 2.09E+06 | 1.29E+06 | 51.00 | 1.00E+06 | 1.29E+06 | 1.00E+06 | 51.00 |
| | AVG | 1.17E+07 | 37.98 | 7.23E+06 | 5.79E+06 | 43.57 | 3.99E+06 | 2.75E+06 | 47.93 | 2.04E+06 | 1.24E+06 | 51.23 | 9.64E+05 | 1.24E+06 | 9.64E+05 | 51.23 |
| | CV | 4.93% | 1.49% | 3.66% | 0.00% | 0.70% | 0.56% | 3.04% | 0.22% | 3.21% | 5.89% | 0.62% | 5.45% | 5.89% | 0.62% | 5.45% |

Continued on Next Page

Page 1 of 2

Table B.3 DSR Results on Long-Term Aged (PAV) Blends

| Blend | @ 10C | | | | @ 16C | | | | @ 22C | | | | @ 28C | | | |
|--|----------|-------|------------------------|----|----------|-------|------------------------|----|----------|-------|------------------------|----|----------|-------|------------------------|----|
| | REP#1 | REP#2 | AVG | CV | REP#1 | REP#2 | AVG | CV | REP#1 | REP#2 | AVG | CV | REP#1 | REP#2 | AVG | CV |
| 50M-R | G*, Pa | delta | G* \times sin(delta) | | G*, Pa | delta | G* \times sin(delta) | | G*, Pa | delta | G* \times sin(delta) | | G*, Pa | delta | G* \times sin(delta) | |
| | 9.13E+06 | 41.58 | 6.06E+06 | | 3.70E+06 | 47.60 | 2.73E+06 | | 1.62E+06 | 52.67 | 1.29E+06 | | 6.55E+05 | 56.31 | 5.45E+05 | |
| | 7.94E+06 | 42.22 | 5.34E+06 | | 3.76E+06 | 47.59 | 2.78E+06 | | 1.63E+06 | 52.32 | 1.29E+06 | | 7.00E+05 | 55.63 | 5.78E+05 | |
| | 8.54E+06 | 41.90 | 5.70E+06 | | 3.73E+06 | 47.60 | 2.75E+06 | | 1.62E+06 | 52.50 | 1.29E+06 | | 6.78E+05 | 55.97 | 5.62E+05 | |
| | 9.80% | 1.08% | 8.92% | | 1.15% | 0.01% | 1.14% | | 0.13% | 0.47% | 0.20% | | 4.75% | 0.86% | 4.18% | |
| 50M-U | 1.31E+07 | 37.74 | 8.00E+06 | | 6.40E+06 | 43.24 | 4.38E+06 | | 2.88E+06 | 47.97 | 2.14E+06 | | 1.27E+06 | 52.30 | 1.01E+06 | |
| | 1.39E+07 | 37.66 | 8.48E+06 | | 6.70E+06 | 43.33 | 4.60E+06 | | 2.98E+06 | 48.38 | 2.23E+06 | | 1.33E+06 | 52.61 | 1.06E+06 | |
| | 1.35E+07 | 37.70 | 8.24E+06 | | 6.55E+06 | 43.29 | 4.49E+06 | | 2.93E+06 | 48.18 | 2.18E+06 | | 1.30E+06 | 52.46 | 1.03E+06 | |
| | 4.30% | 0.15% | 4.17% | | 3.27% | 0.15% | 3.39% | | 2.42% | 0.60% | 2.87% | | 3.46% | 0.42% | 3.75% | |
| 120M-R | 6.91E+06 | 43.07 | 4.72E+06 | | 3.37E+06 | 48.49 | 2.52E+06 | | 1.46E+06 | 52.82 | 1.16E+06 | | 7.10E+05 | 55.60 | 5.85E+05 | |
| | 7.73E+06 | 43.37 | 5.31E+06 | | 3.52E+06 | 48.97 | 2.65E+06 | | 1.53E+06 | 53.16 | 1.23E+06 | | 6.31E+05 | 56.41 | 5.25E+05 | |
| | 7.32E+06 | 43.22 | 5.01E+06 | | 3.44E+06 | 48.73 | 2.59E+06 | | 1.49E+06 | 52.99 | 1.19E+06 | | 6.70E+05 | 56.01 | 5.56E+05 | |
| | 7.91% | 0.49% | 8.30% | | 3.12% | 0.70% | 3.63% | | 3.59% | 0.45% | 3.91% | | 8.32% | 1.02% | 7.64% | |
| 120M-U | 1.24E+07 | 39.38 | 7.89E+06 | | 6.19E+06 | 44.19 | 4.31E+06 | | 3.02E+06 | 47.71 | 2.23E+06 | | 1.41E+06 | 50.54 | 1.09E+06 | |
| | 1.54E+07 | 37.39 | 9.35E+06 | | 7.58E+06 | 42.76 | 5.15E+06 | | 3.34E+06 | 47.68 | 2.47E+06 | | 1.50E+06 | 50.54 | 1.16E+06 | |
| | 1.39E+07 | 38.39 | 8.64E+06 | | 6.88E+06 | 43.48 | 4.74E+06 | | 3.18E+06 | 47.70 | 2.35E+06 | | 1.46E+06 | 50.54 | 1.12E+06 | |
| | 15.10% | 3.67% | 11.99% | | 14.33% | 2.33% | 12.47% | | 7.09% | 0.04% | 7.05% | | 4.27% | 0.00% | 4.27% | |
| Continued from Previous Page | | | | | | | | | | | | | | | | |
| Avg. CV for G* = 5.35% | | | | | | | | | | | | | | | | |
| Avg. CV for delta = 0.88% | | | | | | | | | | | | | | | | |
| Avg. CV for G* \times sin(delta) = 5.20% | | | | | | | | | | | | | | | | |

Table B.4 DSR Results on SUPPLEMENTAL Blends which have been Long-Term Aged.

| Supple- mental Blend | @ 10C | | | | @ 16C | | | | @ 22C | | | | @ 28C | | | |
|----------------------------|--------|----------|------------------------|------------------------|----------|-------|------------------------|------------------------|----------|-------|------------------------|------------------------|--------|----------|------------------------|------------------------|
| | G*, Pa | delta | G* \times sin(delta) | G* \times sin(delta) | G*, Pa | delta | G* \times sin(delta) | G* \times sin(delta) | G*, Pa | delta | G* \times sin(delta) | G* \times sin(delta) | G*, Pa | delta | G* \times sin(delta) | G* \times sin(delta) |
| 16M-PAV | REP#1 | 9.82E+06 | 39.07 | 6.19E+06 | 4.67E+06 | 44.62 | 3.28E+06 | 2.02E+06 | 2.02E+06 | 49.73 | 1.54E+06 | 8.40E+05 | 53.46 | 6.75E+05 | 7.40E+05 | 7.40E+05 |
| | REP#2 | 9.92E+06 | 39.71 | 6.33E+06 | 4.73E+06 | 45.28 | 3.36E+06 | 2.09E+06 | 2.09E+06 | 50.25 | 1.61E+06 | 9.19E+05 | 53.69 | 7.40E+05 | 7.40E+05 | 7.40E+05 |
| | AVG | 9.87E+06 | 39.39 | 6.26E+06 | 4.70E+06 | 44.95 | 3.32E+06 | 2.05E+06 | 2.05E+06 | 49.99 | 1.57E+06 | 8.79E+05 | 53.58 | 7.08E+05 | 7.08E+05 | 7.08E+05 |
| | CV | 0.65% | 1.15% | 1.61% | 0.91% | 1.04% | 1.73% | 2.40% | 2.40% | 0.74% | 2.94% | 6.34% | 0.30% | 6.55% | 6.55% | 6.55% |
| 40M-PAV | REP#1 | 1.09E+07 | 37.76 | 6.67E+06 | 5.34E+06 | 43.73 | 3.69E+06 | 2.42E+06 | 2.42E+06 | 48.43 | 1.81E+06 | 1.09E+06 | 51.53 | 8.50E+05 | 8.50E+05 | 8.50E+05 |
| | REP#2 | 1.18E+07 | 37.79 | 7.25E+06 | 5.61E+06 | 43.69 | 3.87E+06 | 2.50E+06 | 2.50E+06 | 48.34 | 1.87E+06 | 1.10E+06 | 51.34 | 8.62E+05 | 8.62E+05 | 8.62E+05 |
| | AVG | 1.14E+07 | 37.78 | 6.96E+06 | 5.47E+06 | 43.71 | 3.78E+06 | 2.46E+06 | 2.46E+06 | 48.39 | 1.84E+06 | 1.09E+06 | 51.44 | 8.56E+05 | 8.56E+05 | 8.56E+05 |
| | CV | 5.85% | 0.06% | 5.90% | 3.53% | 0.06% | 3.47% | 2.44% | 2.44% | 0.13% | 2.34% | 1.78% | 0.26% | 0.99% | 0.99% | 0.99% |
| 50M-PAV | REP#1 | 1.06E+07 | 38.17 | 6.56E+06 | 5.03E+06 | 44.21 | 3.51E+06 | 2.28E+06 | 2.28E+06 | 48.62 | 1.71E+06 | 1.03E+06 | 51.44 | 8.04E+05 | 8.04E+05 | 8.04E+05 |
| | REP#2 | 1.12E+07 | 37.86 | 6.89E+06 | 5.55E+06 | 43.73 | 3.84E+06 | 2.47E+06 | 2.47E+06 | 48.64 | 1.85E+06 | 1.09E+06 | 51.64 | 8.56E+05 | 8.56E+05 | 8.56E+05 |
| | AVG | 1.09E+07 | 38.02 | 6.72E+06 | 5.29E+06 | 43.97 | 3.67E+06 | 2.38E+06 | 2.38E+06 | 48.63 | 1.78E+06 | 1.06E+06 | 51.54 | 8.30E+05 | 8.30E+05 | 8.30E+05 |
| | CV | 3.93% | 0.58% | 3.44% | 6.89% | 0.77% | 6.27% | 5.66% | 5.66% | 0.03% | 5.68% | 4.25% | 0.27% | 4.44% | 4.44% | 4.44% |
| 120M-PAV | REP#1 | 8.82E+06 | 40.50 | 5.73E+06 | 4.64E+06 | 45.61 | 3.32E+06 | 2.25E+06 | 2.25E+06 | 49.67 | 1.72E+06 | 1.06E+06 | 52.46 | 8.39E+05 | 8.39E+05 | 8.39E+05 |
| | REP#2 | 1.03E+07 | 39.44 | 6.57E+06 | 5.00E+06 | 44.81 | 3.53E+06 | 2.18E+06 | 2.18E+06 | 49.60 | 1.66E+06 | 9.13E+05 | 52.61 | 7.25E+05 | 7.25E+05 | 7.25E+05 |
| | AVG | 9.58E+06 | 39.97 | 6.16E+06 | 4.82E+06 | 45.21 | 3.42E+06 | 2.22E+06 | 2.22E+06 | 49.64 | 1.69E+06 | 9.85E+05 | 52.54 | 7.82E+05 | 7.82E+05 | 7.82E+05 |
| | CV | 11.19% | 1.88% | 9.63% | 5.34% | 1.25% | 4.36% | 2.42% | 2.42% | 0.10% | 2.49% | 10.44% | 0.20% | 10.30% | 10.30% | 10.30% |
| 50M-TFO | REP#1 | 9.61E+06 | 39.79 | 6.15E+06 | 4.12E+06 | 46.07 | 2.97E+06 | 1.65E+06 | 1.65E+06 | 51.43 | 1.29E+06 | 6.76E+05 | 55.12 | 5.55E+05 | 5.55E+05 | 5.55E+05 |
| | REP#2 | 9.04E+06 | 39.71 | 5.77E+06 | 4.09E+06 | 46.18 | 2.95E+06 | 1.70E+06 | 1.70E+06 | 51.36 | 1.33E+06 | 7.10E+05 | 54.82 | 5.80E+05 | 5.80E+05 | 5.80E+05 |
| | AVG | 9.32E+06 | 39.75 | 5.96E+06 | 4.11E+06 | 46.13 | 2.96E+06 | 1.68E+06 | 1.68E+06 | 51.40 | 1.31E+06 | 6.93E+05 | 54.97 | 5.67E+05 | 5.67E+05 | 5.67E+05 |
| | CV | 4.37% | 0.14% | 4.49% | 0.52% | 0.17% | 0.39% | 2.30% | 2.30% | 0.10% | 2.23% | 3.40% | 0.39% | 3.14% | 3.14% | 3.14% |

APPENDIX C

Individual BBR and DTT Results

The results of all BBR and DTT tests under this test plan are tabulated in this appendix. Table C.1 lists the S and m values of all three BBR sample repetitions, as well as an average, standard deviation and CV, for all 11 blends tested. Table C.2 lists the ϵ_f and peak stress of all 12 DTT sample repetitions, as well as an average and standard deviation of ϵ_f , for the same 11 blends.

Table C.1 BBR Results, @ -18C

| Blend | | REP#1 | REP#2 | REP#3 | AVG. | Std. Dev. | CV |
|---------|----------|-------|-------|-------|-------|-----------|------|
| AC-10 | S, MPa | 287 | 285 | 275 | 282.3 | 6.4 | 2.3% |
| | <i>m</i> | 0.31 | 0.31 | 0.30 | 0.307 | 0.006 | 1.9% |
| AC-30 | S, MPa | 435 | 417 | 429 | 427.0 | 9.2 | 2.1% |
| | <i>m</i> | 0.25 | 0.25 | 0.24 | 0.247 | 0.006 | 2.3% |
| 16M-R | S, MPa | 124 | 128 | 132 | 128.0 | 4.0 | 3.1% |
| | <i>m</i> | 0.33 | 0.32 | 0.32 | 0.323 | 0.006 | 1.8% |
| 40M-R | S, MPa | 130 | 134 | 136 | 133.3 | 3.1 | 2.3% |
| | <i>m</i> | 0.32 | 0.32 | 0.34 | 0.327 | 0.012 | 3.5% |
| 50M-R | S, MPa | 109 | 114 | 114 | 112.3 | 2.9 | 2.6% |
| | <i>m</i> | 0.33 | 0.33 | 0.34 | 0.333 | 0.006 | 1.7% |
| 120M-R | S, MPa | 123 | 125 | 125 | 124.3 | 1.2 | 0.9% |
| | <i>m</i> | 0.34 | 0.34 | 0.34 | 0.340 | 0.000 | 0.0% |
| 16M-U | S, MPa | 175 | 189 | 175 | 179.7 | 8.1 | 4.5% |
| | <i>m</i> | 0.30 | 0.30 | 0.30 | 0.300 | 0.000 | 0.0% |
| 40M-U | S, MPa | 170 | 203 | 190 | 187.7 | 16.6 | 8.9% |
| | <i>m</i> | 0.29 | 0.29 | 0.30 | 0.293 | 0.006 | 2.0% |
| 50M-U | S, MPa | 186 | 197 | 211 | 198.0 | 12.5 | 6.3% |
| | <i>m</i> | 0.30 | 0.29 | 0.30 | 0.297 | 0.006 | 1.9% |
| 120M-U | S, MPa | 198 | 198 | 194 | 196.7 | 2.3 | 1.2% |
| | <i>m</i> | 0.30 | 0.30 | 0.30 | 0.300 | 0.000 | 0.0% |
| 50M-TFO | S, MPa | 121 | 120 | 129 | 123.3 | 4.9 | 4.0% |
| | <i>m</i> | 0.31 | 0.31 | 0.31 | 0.310 | 0.000 | 0.0% |

Table C.2 Direct Tension Results, @ -18C

| Blend | REP1 | REP2 | REP3 | REP4 | REP5 | REP6 | REP7 | REP8 | REP9 | REP10 | REP11 | REP12 | AVG. | Std. Dev. |
|----------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------------|
| AC-10 | 0.227 | 0.203 | 0.211 | 0.233 | 0.541 | 0.129 | 0.271 | 0.128 | 0.259 | 0.425 | 0.357 | 0.154 | 0.261 | 0.124 |
| PK STRESS, MPa | 1.523 | 1.153 | 1.656 | 1.348 | 2.468 | 1.393 | 1.021 | 0.733 | 1.196 | 1.916 | 1.738 | 1.088 | 1.436 | |
| AC-30 | 0.090 | 0.043 | 0.130 | 0.076 | 0.096 | 0.158 | 0.104 | 0.132 | 0.125 | 0.072 | 0.097 | 0.147 | 0.106 | 0.034 |
| PK STRESS, MPa | 0.810 | 0.754 | 1.245 | 1.053 | 1.458 | 1.296 | 1.053 | 1.303 | 1.114 | 0.706 | 0.894 | 1.383 | 1.089 | |
| 16M-R | 0.361 | 0.384 | 0.384 | 0.310 | 0.543 | 0.572 | 0.581 | 0.415 | 0.423 | 0.503 | 0.530 | 0.446 | 0.454 | 0.090 |
| PK STRESS, MPa | 1.263 | 1.400 | 1.246 | 1.177 | 1.493 | 1.583 | 1.500 | 1.358 | 1.472 | 1.343 | 1.235 | 1.136 | 1.351 | |
| 40M-R | 0.371 | 0.385 | 0.296 | 0.402 | 0.279 | 0.545 | 0.602 | 0.737 | 0.561 | 0.699 | 0.347 | 0.499 | 0.477 | 0.153 |
| PK STRESS, MPa | 1.221 | 1.269 | 0.895 | 1.110 | 1.033 | 1.446 | 1.705 | 1.232 | 1.445 | 1.696 | 1.145 | 1.020 | 1.268 | |
| 50M-R | 0.686 | 0.496 | 0.389 | 0.511 | 0.309 | 0.519 | 0.410 | 0.455 | 0.493 | 0.581 | 0.462 | 0.421 | 0.478 | 0.096 |
| PK STRESS, MPa | 1.372 | 1.073 | 0.898 | 1.271 | 1.125 | 1.364 | 1.094 | 1.152 | 1.338 | 1.521 | 1.336 | 1.307 | 1.238 | |
| 120M-R | 2.118 | 1.928 | 2.127 | 1.970 | 2.044 | 1.781 | 1.606 | 1.648 | 2.044 | 1.879 | 1.423 | 1.642 | 1.851 | 0.229 |
| PK STRESS, MPa | 2.611 | 2.781 | 3.073 | 2.917 | 3.225 | 2.833 | 2.454 | 2.951 | 2.860 | 2.980 | 2.497 | 2.634 | 2.818 | |
| 16M-U | 0.051 | 0.045 | 0.191 | 0.082 | 0.100 | 0.149 | 0.055 | 0.097 | 0.075 | 0.095 | 0.087 | 0.067 | 0.091 | 0.042 |
| PK STRESS, MPa | 0.544 | 0.590 | 0.999 | 0.716 | 0.754 | 0.656 | 0.462 | 0.769 | 0.110 | 0.639 | 0.727 | 0.570 | 0.628 | |
| 40M-U | 0.197 | 0.184 | 0.183 | 0.178 | 0.115 | 0.178 | 0.213 | 0.159 | 0.134 | 0.205 | 0.208 | 0.123 | 0.173 | 0.034 |
| PK STRESS, MPa | 0.897 | 0.932 | 0.990 | 1.011 | 0.775 | 0.990 | 1.055 | 0.736 | 0.707 | 0.757 | 0.576 | 0.733 | 0.847 | |
| 50M-U | 0.205 | 0.212 | 0.183 | 0.143 | 0.213 | 0.206 | 0.125 | 0.264 | 0.122 | 0.210 | 0.161 | 0.212 | 0.188 | 0.042 |
| PK STRESS, MPa | 0.953 | 0.969 | 0.916 | 0.805 | 0.952 | 0.991 | 0.756 | 0.876 | 0.729 | 0.584 | 0.770 | 1.023 | 0.860 | |
| 120M-U | 0.571 | 0.304 | 0.210 | 0.290 | 0.296 | 0.103 | 0.324 | 0.298 | 0.166 | 0.243 | 0.187 | 0.321 | 0.276 | 0.116 |
| PK STRESS, MPa | 1.503 | 1.203 | 1.177 | 1.340 | 1.359 | 0.851 | 1.259 | 1.090 | 0.717 | 0.987 | 0.968 | 1.323 | 1.148 | |
| 50M-TFO | 0.490 | 0.122 | 0.205 | 0.126 | 0.455 | 0.493 | 0.581 | 0.462 | 0.916 | 0.421 | 0.686 | | 0.451 | 0.238 |
| PK STRESS, MPa | 1.205 | 0.964 | 0.844 | 0.910 | 1.152 | 1.338 | 1.521 | 1.336 | 1.415 | 1.307 | 1.372 | 0.000 | 1.215 | |

APPENDIX D

Individual RM Test Results

The results of all individual RM testing are tabulated in this appendix. Table D.1 presents the results for the 4% VTM samples, Table D.2 for the 7% VTM samples before LT aging, and Table D.3 for the same 7% samples after LT aging. In each table, the actual VTM of each sample is listed as well as both the uncorrected and corrected (to 15% ITS) RM values at all three temperatures. Table D.4 shows the individual aging ratios of the 7% VTM samples.

Table D.1 RM Results on 4% VTM Samples

| Mix | Sample ID # | VTM | @ 40 degrees C | | @ 25 degrees C | | @ 5 degrees C |
|----------------|-------------|------------|-----------------|------------|-------------------|-----------------|-------------------------|
| | | | Uncorr. RM, MPa | % ITS used | Corrected RM, MPa | Uncorr. RM, MPa | (no correction) RM, MPa |
| CNTRL | 4 | 3.2 | 1187 | 14.7 | 1171 | 4526 | 26389 |
| CNTRL | 14 | 3.3 | 1293 | 14.3 | 1257 | 5234 | 34084 |
| CNTRL | 19 | 3.3 | 1178 | 14.7 | 1161 | 4152 | 27803 |
| average | | 3.3 | 1219 | | 1197 | 4637 | 29425 |
| 16M Wet | 5 | 5.0 | 821 | 13.5 | 768 | 2983 | 18290 |
| 16M Wet | 8 | 3.7 | 931 | 13.5 | 870 | 2906 | 18319 |
| 16M Wet | 13 | 3.1 | 867 | 13.5 | 811 | 3221 | 16232 |
| average | | 3.9 | 873 | | 816 | 3037 | 17614 |
| 16M Dry | 3 | 3.5 | 901 | 12.8 | 818 | 2902 | 20928 |
| 16M Dry | 5 | 3.8 | 765 | 12.6 | 686 | 2308 | 13267 |
| 16M Dry | 9 | 3.5 | 766 | 12.6 | 687 | 2645 | 15703 |
| average | | 3.6 | 811 | | 730 | 2618 | 16632 |
| 80M Wet | 3 | 3.6 | 925 | 12.5 | 828 | 2052 | 19579 |
| 80M Wet | 7 | 4.5 | 819 | 12.8 | 742 | 1897 | 17653 |
| 80M Wet | 8 | 3.6 | 852 | 13.0 | 781 | 2182 | 17953 |
| average | | 3.9 | 866 | | 784 | 2044 | 18395 |
| 80M Dry | 10 | 4.3 | 860 | 12.1 | 756 | 2591 | 20307 |
| 80M Dry | 11 | 3.5 | 1034 | 12.1 | 909 | 3061 | 18672 |
| 80M Dry | 12 | 3.5 | 1012 | 12.1 | 890 | 2966 | 22896 |
| average | | 3.8 | 969 | | 852 | 2873 | 20625 |

Table D.2 RM Results on 7% VTM Samples Before LT Aging

| Mix | Sample ID # | VTM | @ 40 degrees C | | | @ 25 degrees C | | | @ 5 degrees C |
|----------------|-------------|------------|-----------------|------------|-------------------|-----------------|------------|-------------------|-------------------------|
| | | | Uncorr. RM, MPa | % ITS used | Corrected RM, MPa | Uncorr. RM, MPa | % ITS used | Corrected RM, MPa | (no correction) RM, MPa |
| CNTRL | 10 | 6.7 | 956 | 15.0 | 957 | 3480 | 15.0 | 3477 | 27932 |
| CNTRL | 12 | 6.9 | 992 | 15.2 | 999 | 2867 | 15.6 | 2907 | 28381 |
| CNTRL | 13 | 7.0 | 873 | 14.9 | 869 | 3159 | 14.8 | 3146 | 29424 |
| average | | 6.9 | 940 | | 942 | 3169 | | 3176 | 28579 |
| 16M Wet | 15 | 7.2 | 621 | 15.4 | 631 | 1477 | 13.8 | 1434 | 13451 |
| 16M Wet | 17 | 6.7 | 637 | 15.4 | 647 | 1468 | 14.0 | 1433 | 18877 |
| 16M Wet | 21 | 6.7 | 653 | 15.4 | 663 | 1292 | 13.8 | 1254 | 17626 |
| average | | 6.9 | 637 | | 647 | 1412 | | 1373 | 16651 |
| 16M Dry | 11 | 6.6 | 733 | 16.6 | 782 | 1665 | 15.7 | 1693 | 14088 |
| 16M Dry | 12 | 7.1 | 631 | 16.6 | 673 | 1657 | 15.8 | 1690 | 14414 |
| 16M Dry | 21 | 7.3 | 614 | 16.6 | 655 | 1305 | 15.4 | 1315 | 14695 |
| average | | 7.0 | 659 | | 703 | 1542 | | 1566 | 14399 |
| 80M Wet | 14 | 6.9 | 637 | 14.7 | 629 | 1640 | 14.7 | 1630 | 16630 |
| 80M Wet | 19 | 7.1 | 689 | 15.1 | 690 | 1642 | 14.7 | 1629 | 17674 |
| 80M Wet | 20 | 6.9 | 693 | 15.1 | 695 | 1652 | 14.9 | 1650 | 12199 |
| average | | 7.0 | 673 | | 671 | 1645 | | 1636 | 15501 |
| 80M Dry | 1 | 7.2 | 622 | 15.3 | 630 | 1454 | 15.1 | 1456 | 16241 |
| 80M Dry | 3 | 7.2 | 736 | 14.9 | 734 | 1325 | 14.8 | 1319 | 16662 |
| 80M Dry | 13 | 6.4 | 644 | 15.1 | 648 | 1228 | 14.8 | 1223 | 13895 |
| average | | 6.9 | 667 | | 670 | 1336 | | 1333 | 15599 |

Table D.3 RM Results on 7% VTM Samples After LT Aging

| Mix | Sample ID # | VTM | @ 40 degrees C | | @ 25 degrees C | | @ 5 degrees C |
|----------------|-------------|------------|-----------------|------------|-------------------|-----------------|-------------------------|
| | | | Uncorr. RM, MPa | % ITS used | Corrected RM, MPa | Uncorr. RM, MPa | (no correction) RM, MPa |
| CNTRL | 10 | 6.7 | 1134 | 13.9 | 1081 | 4560 | 28353 |
| CNTRL | 12 | 6.9 | 1302 | 14.5 | 1275 | 4445 | 28261 |
| CNTRL | 13 | 7.0 | 892 | 14.2 | 864 | 4175 | 23237 |
| average | | 6.9 | 1109 | | 1073 | 4393 | 26617 |
| 16M Wet | 15 | 7.2 | 781 | 14.2 | 753 | 2090 | 13608 |
| 16M Wet | 17 | 6.7 | 719 | 14.2 | 693 | 1919 | 12766 |
| 16M Wet | 21 | 6.7 | 768 | 14.2 | 741 | 2169 | 15721 |
| average | | 6.9 | 756 | | 729 | 2059 | 14031 |
| 16M Dry | 11 | 6.6 | 814 | 12.1 | 714 | 1914 | 13587 |
| 16M Dry | 12 | 7.1 | 639 | 12.4 | 570 | 1873 | 14738 |
| 16M Dry | 21 | 7.3 | 707 | 12.6 | 635 | 1568 | 12540 |
| average | | 7.0 | 720 | | 640 | 1785 | 13622 |
| 80M Wet | 14 | 6.9 | 838 | 12.8 | 760 | 1908 | 16434 |
| 80M Wet | 19 | 7.1 | 797 | 12.7 | 718 | 2017 | 17092 |
| 80M Wet | 20 | 6.9 | 885 | 12.8 | 803 | 1877 | 18041 |
| average | | 7.0 | 840 | | 760 | 1934 | 17189 |
| 80M Dry | 1 | 7.2 | 813 | 12.6 | 728 | 2048 | 16770 |
| 80M Dry | 3 | 7.2 | 872 | 12.6 | 781 | 2309 | 18426 |
| 80M Dry | 13 | 6.4 | 907 | 12.7 | 818 | 2070 | 14472 |
| average | | 6.9 | 864 | | 776 | 2142 | 16556 |

Table D.4 Long Term Aging Ratios of Samples

| | | Rm' = Corrected RM after long term aging Rm = Corrected RM before long term aging | | |
|---------|-----------------|--|--------------|-------------|
| MIX | SAMPLE ID # | Rm'/Rm @ 40C | Rm'/Rm @ 25C | Rm'/Rm @ 5C |
| CNTRL | 10 | 1.13 | 1.30 | 1.02 |
| CNTRL | 12 | 1.28 | 1.43 | 1.00 |
| CNTRL | 13 | 0.99 | 1.24 | 0.79 |
| | Average | 1.14 | 1.32 | 0.93 |
| | Stnd Dev | 0.14 | 0.10 | 0.12 |
| 16M Wet | 15 | 1.19 | 1.44 | 1.01 |
| 16M Wet | 17 | 1.07 | 1.32 | 0.68 |
| 16M Wet | 21 | 1.12 | 1.71 | 0.89 |
| | Average | 1.13 | 1.48 | 0.84 |
| | Stnd Dev | 0.06 | 0.20 | 0.17 |
| 16M Dry | 11 | 0.91 | 1.08 | 0.96 |
| 16M Dry | 12 | 0.85 | 1.05 | 1.02 |
| 16M Dry | 21 | 0.97 | 1.13 | 0.85 |
| | Average | 0.91 | 1.08 | 0.95 |
| | Stnd Dev | 0.06 | 0.04 | 0.09 |
| 80M Wet | 14 | 1.21 | 1.13 | 0.99 |
| 80M Wet | 19 | 1.04 | 1.19 | 0.97 |
| 80M Wet | 20 | 1.16 | 1.10 | 1.48 |
| | Average | 1.13 | 1.14 | 1.11 |
| | Stnd Dev | 0.09 | 0.05 | 0.29 |
| 80M Dry | 1 | 1.16 | 1.33 | 1.03 |
| 80M Dry | 3 | 1.06 | 1.66 | 1.11 |
| 80M Dry | 13 | 1.26 | 1.61 | 1.04 |
| | Average | 1.16 | 1.53 | 1.06 |
| | Stnd Dev | 0.10 | 0.18 | 0.04 |

APPENDIX E

Individual IT and Creep Test Results

The results of all individual IT tests are in Table E.1. This includes the ITS, ϵ_f , and actual VTM of each sample. The individual creep test results are in Table E.2. This includes the permanent ϵ , rebound, VTM and actual binder content of each sample.

Table E.1 Individual Indirect Tension Test Results

| 4% VTM samples before Rm testing | | | | |
|---|-----------|------------|--------------|-------------------|
| Mix | Smpl ID # | VTM | ITS, MPa | Failure Strain, % |
| CNTRL | 16 | 3.2 | 2.021 | 0.68 |
| 16M Wet | 11 | 4.3 | 1.139 | 0.59 |
| 16M Dry | 10 | 3.4 | 1.129 | 0.63 |
| 80M Wet | 2 | 3.5 | 1.290 | 0.59 |
| 80M Dry | 7 | 3.4 | 1.188 | 0.59 |
| 4% VTM samples after Rm testing | | | | |
| Mix | Smpl ID # | VTM | ITS, MPa | Failure Strain, % |
| CNTRL | 4 | 3.2 | 2.362 | 0.72 |
| CNTRL | 14 | 3.3 | 2.186 | 0.68 |
| CNTRL | 19 | 3.3 | 2.282 | 0.68 |
| average | | 3.3 | 2.277 | 0.69 |
| 16M Wet | 5 | 5.0 | 1.209 | 0.72 |
| 16M Wet | 8 | 3.7 | 1.389 | 0.63 |
| 16M Wet | 13 | 3.1 | 1.461 | 0.72 |
| average | | 3.9 | 1.353 | 0.69 |
| 16M Dry | 3 | 3.5 | 1.441 | 0.59 |
| 16M Dry | 5 | 3.8 | 1.381 | 0.68 |
| 16M Dry | 9 | 3.5 | 1.477 | 0.63 |
| average | | 3.6 | 1.433 | 0.63 |
| 80M Wet | 3 | 3.6 | 1.597 | 0.63 |
| 80M Wet | 7 | 4.5 | 1.485 | 0.63 |
| 80M Wet | 8 | 3.6 | 1.377 | 0.63 |
| average | | 3.9 | 1.486 | 0.63 |
| 80M Dry | 10 | 4.3 | 1.505 | 0.63 |
| 80M Dry | 11 | 3.5 | 1.543 | 0.63 |
| 80M Dry | 12 | 3.5 | 1.618 | 0.63 |
| average | | 3.8 | 1.555 | 0.63 |

Continued on Next Page

Page 1 of 2

| 7% VTM samples before LT aging | | | | |
|---------------------------------------|-----------|------------|------------------|-------------------|
| Mix | Smpl ID # | VTM | ITS, MPa | Failure Strain, % |
| CNTRL | 9 | 6.1 | 1.405 | 0.72 |
| CNTRL | 20 | 7.5 | 1.403 | 0.68 |
| CNTRL | 21 | 7.5 | 1.511 | 0.72 |
| average | | 7.0 | 1.440 | 0.71 |
| 16M Wet | 16 | 6.5 | 0.866 | 0.86 |
| 16M Wet | 18 | 7.8 | 0.855 | 0.72 |
| 16M Wet | 20 | 6.4 | 0.936 | 0.72 |
| average | | 6.9 | 0.886 | 0.77 |
| 16M Dry | 13 | 7.9 | 0.738 | 0.99 |
| 16M Dry | 15 | 7.9 | 0.739 | 0.81 |
| 16M Dry | 23 | 7.3 | 0.810 | 0.81 |
| average | | 7.7 | 0.762 | 0.87 |
| 80M Wet | 15 | 6.7 | 0.996 | 0.68 |
| 80M Wet | 17 | 6.5 | 0.972 | 0.68 |
| 80M Wet | 21 | 6.9 | 0.898 | 0.68 |
| average | | 6.7 | 0.955 | 0.68 |
| 80M Dry | 2 | 7.3 | 0.868 | 0.63 |
| 80M Dry | 14 | 6.4 | 0.971 | 0.72 |
| 80M Dry | 15 | 6.2 | 0.969 | 0.68 |
| average | | 6.6 | 0.936 | 0.68 |
| 7% VTM samples after LT aging | | | | |
| Mix | Smpl ID | VTM, % | Peak Stress, MPa | T Strain, % |
| CNTRL | 10 | 6.7 | 1.964 | 0.81 |
| CNTRL | 12 | 6.9 | 1.948 | 0.86 |
| CNTRL | 13 | 7.0 | 1.829 | 0.90 |
| average | | 6.9 | 1.913 | 0.86 |
| 16M Wet | 15 | 7.2 | 1.241 | 0.77 |
| 16M Wet | 17 | 6.7 | 1.187 | 0.77 |
| 16M Wet | 21 | 6.7 | 1.184 | 0.77 |
| average | | 6.9 | 1.204 | 0.77 |
| 16M Dry | 11 | 6.6 | 1.200 | 0.77 |
| 16M Dry | 12 | 7.1 | 1.107 | 0.86 |
| 16M Dry | 21 | 7.3 | 1.012 | 0.81 |
| average | | 7.0 | 1.106 | 0.81 |
| 80M Wet | 14 | 6.9 | 1.450 | 0.72 |
| 80M Wet | 19 | 7.1 | 1.371 | 0.68 |
| 80M Wet | 20 | 6.9 | 1.334 | 0.68 |
| average | | 7.0 | 1.385 | 0.69 |
| 80M Dry | 1 | 7.2 | 1.389 | 0.59 |
| 80M Dry | 3 | 7.2 | 1.422 | 0.59 |
| 80M Dry | 13 | 6.4 | 1.342 | 0.63 |
| average | | 6.9 | 1.384 | 0.60 |

Continued from Previous Page

Page 2 of 2

Table E.2 Individual Creep Test Results

| Mix | Sample ID # | Actual Binder % | % Binder Over Opt. | VTM | Permanent Creep Strain | Rebound |
|----------------|-------------|-----------------|--------------------|------------|------------------------|-------------|
| CNTRL | 1 | 4.1 | 0 | 3.6 | 1.78 | 0.04 |
| CNTRL | 3 | 4.1 | 0 | 4.1 | 1.37 | 0.06 |
| CNTRL | 7 | 4.1 | 0 | 3.7 | 1.13 | 0.05 |
| average | | | | 3.8 | 1.43 | 0.05 |
| 16M Wet | 9 | 5.0 | 0 | 3.9 | 1.64 | 0.03 |
| 16M Wet | 22 | 5.0 | 0 | 3.6 | 2.15 | 0.06 |
| 16M Wet | 23 | 5.0 | 0 | 4.2 | 3.65 | 0.04 |
| average | | | | 3.9 | 2.48 | 0.04 |
| 16M Dry | 1 | 5.0 | 0 | 3.2 | 1.78 | 0.04 |
| 16M Dry | 4 | 5.0 | 0 | 4.3 | 1.93 | 0.05 |
| 16M Dry | 6 | 5.0 | 0 | 3.5 | 1.07 | 0.01 |
| average | | | | 3.7 | 1.59 | 0.03 |
| 80M Wet | 4 | 4.4 | 0 | 3.7 | 1.29 | 0.05 |
| 80M Wet | 6 | 4.4 | 0 | 4.0 | 2.70 | 0.05 |
| 80M Wet | 9 | 4.4 | 0 | 3.7 | 1.79 | 0.03 |
| average | | | | 3.8 | 1.93 | 0.04 |
| 80M Dry | 4 | 4.4 | 0 | 4.2 | 1.50 | 0.04 |
| 80M Dry | 6 | 4.4 | 0 | 3.6 | 1.56 | 0.02 |
| 80M Dry | 8 | 4.4 | 0 | 3.7 | 1.21 | 0.03 |
| average | | | | 3.8 | 1.42 | 0.03 |
| CNTRL | 4.5-1 | 4.5 | 0.4 | 2.1 | 2.26 | 0.05 |
| CNTRL | 4.5-1 | 4.5 | 0.4 | 3.4 | 1.40 | 0.05 |
| CNTRL | 4.5-1 | 4.5 | 0.4 | 2.0 | 2.93 | 0.06 |
| average | | | | 2.5 | 2.20 | 0.05 |
| 16M Wet | 5.5-1 | 5.5 | 0.5 | 2.9 | 2.82 | 0.04 |
| 16M Wet | 5.5-2 | 5.5 | 0.5 | 3.0 | 1.80 | 0.01 |
| 16M Wet | 5.5-3 | 5.5 | 0.5 | 3.2 | 1.47 | 0.01 |
| average | | | | 3.0 | 2.03 | 0.02 |
| 16M Dry | 5.5-1 | 5.5 | 0.5 | 2.2 | 2.30 | 0.04 |
| 16M Dry | 5.5-2 | 5.5 | 0.5 | 2.2 | 3.22 | 0.04 |
| 16M Dry | 5.5-3 | 5.5 | 0.5 | 2.9 | 3.18 | 0.02 |
| average | | | | 2.4 | 2.90 | 0.03 |
| 80M Wet | 5.0-1 | 5.0 | 0.6 | 2.6 | 1.92 | 0.04 |
| 80M Wet | 5.0-2 | 5.0 | 0.6 | 2.5 | 1.89 | 0.04 |
| 80M Wet | 5.0-3 | 5.0 | 0.6 | 2.6 | 1.81 | 0.04 |
| average | | | | 2.6 | 1.87 | 0.04 |
| 80M Dry | 5.0-1 | 5.0 | 0.6 | 2.6 | 2.55 | 0.05 |
| 80M Dry | 5.0-2 | 5.0 | 0.6 | 2.5 | 2.11 | 0.04 |
| 80M Dry | 5.0-3 | 5.0 | 0.6 | 1.9 | 2.00 | 0.06 |
| average | | | | 2.3 | 2.22 | 0.05 |